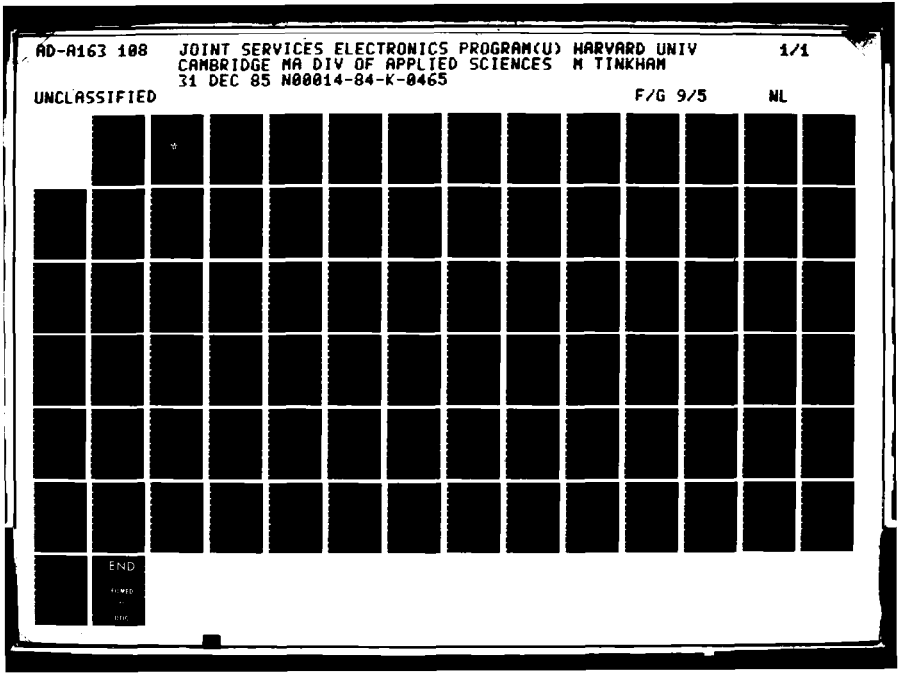
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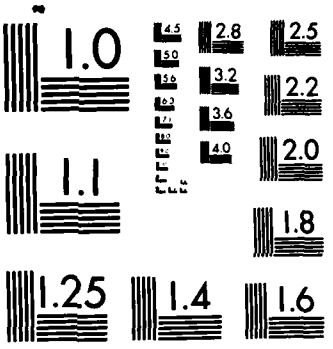

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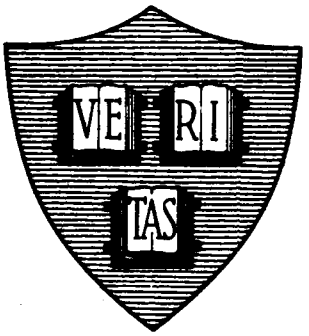

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N00014-84-K-0465

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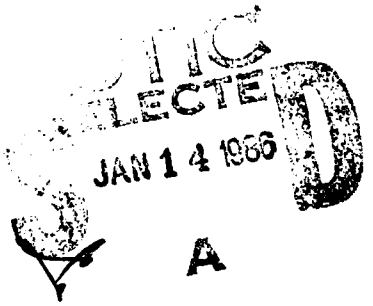

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An annual report of the JSEP (Joint Services Electronic Program) in solid state electronics, quantum electronics, information electronics, control and optimization, and electromagnetic phenomenon is presented. Results of the research to date are summarized and significant accomplishments are discussed.

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April 1, 1985 - December 31, 1985

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INTRODUCTION

To bring our reporting cycle into step with the new JSEP schedule, this report covers progress made in only the 9-month period 1 April, 1985 to 31 December, 1985 for the eleven research units funded under the Joint Services Electronics Program at Harvard University. It is broken down into four major divisions of electronic research--*solid state electronics*, *quantum electronics*, *information electronics*, and *electromagnetic phenomena*. It also includes a report of *Significant Accomplishments* which contains selected noteworthy results. These are: "Ultra-High-Speed Real-Time Optical Processing Via Convolution and Cross-Correlation in Inhomogeneously Broadened Optical Materials" by Research Unit 6 and "Electromagnetic Missiles" by Research Unit 11.

CONTENTS

II. QUANTUM ELECTRONICS

III. INFORMATION ELECTRONICS, CONTROL AND OPTIMIZATION

IV. ELECTROMAGNETIC PHENOMENA

V. SIGNIFICANT ACCOMPLISHMENT REPORTS

I. SOLID STATE ELECTRONICS

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Prof. P.S. Pershan
Prof. M. Tinkham
Asst. Prof. C.J. Lobb
Assoc. Prof. R.M. Westervelt
Dr. H. Akoh
Dr. J.U. Free
Dr. K.C. Hass
Dr. J. Hanna
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Mr. Q. Hu
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Mr. A. Johnson
Mr. B. Larson
Mr. R. Lempert
Ms. S. Lee
Mr. I. Tidswell

I.1 Electronic Structure and Magnetic Properties of Diluted Magnetic Semiconductors (DMS).

H. Ehrenreich, K.C. Hass, B. Larson, and R. Lempert, Contract N00014-84-K-0465; Research Unit 1.

The group has been investigating hypothetical zinc-blende MnTe in the Type I and Type II anti-ferromagnetic states as well as the disordered magnetic state. These calculations are complemented by ASW first principles computations. These results serve as an input for careful empirical tight-binding calculations for disordered CdMnTe and permit investigation of the pressure-dependence of the electronic levels and the cohesive energy of the alloy. They also serve as a basis for the investigation of the magnetic properties as described below.

The fundamental exchange constants responsible for the magnetic properties of diluted magnetic semiconductors are also being investigated [1]. The d-d exchange interaction has been shown to be dominated by superexchange and to be far more important than other exchange interactions. The strength of the sp-d exchange interaction, which determines the optical properties of practical interest in the band-gap region and the properties of magnetic polarons has also been determined. The results appear to be in good agreement with experiment.

Reference:

1. B.E. Larson, K.C. Hass, H. Ehrenreich, and A.E. Carlsson, "Exchange Mechanisms in Diluted Magnetic Semiconductors," *Solid State Commun.* **56**, 4, 347 (1985).

I.2 Magnetization Steps in CdMnTe. K.C. Hass, B.E. Larson, and H. Ehrenreich, Contract N00014-84-K-0465; Research Unit 1.

More recently, the magnetization steps in CdMnTe observed at the National Magnet Lab. have been interpreted [1]. These are exhibited in measurements of the magnetization as a function of magnetic field at very high field of R.L. Aggarwal and result from spin flips modified by nearest-neighbor exchange interactions. Magnetization steps have been observed in alloys having low Mn concentrations. Our calculations are being extended to higher concentrations using CPA techniques. The experimental observations require higher fields. Despite experimental difficulties, however, it is important to understand these effects in order to make a quantitative determination of the strength of the internal magnetic fields which affect both transport and optical properties.

Reference:

1. B.E. Larson, K.C. Hass, and R.L. Aggarwal, "Effects of Internal Exchange Fields on Magnetization Steps in Diluted Magnetic Semiconductors," (accepted for publication in *Phys. Rev.* **B**).

I.3 Semiconducting Pseudobinary Alloys. H. Ehrenreich, R. Lempert, and K.C. Hass, Contract N00014-84-K-0465; Research Unit 1.

The MCPA has been applied to the anionic II-VI alloy Zn(Se,Te) and the cationic III-V alloy (In, Ga)As [1]. Detailed comparisons have been made of the energy levels of chalcopyrite and corresponding disordered structure for the II-VI compound in order to investigate the possible effects of short-range order. The ordered crystal approximation is not expected to be valid in the understanding of band edge properties since effects such as disorder-induced bowing and disorder scattering on the electron mobility are neglected. These investigations have also shown that the MCPA is a better approximation to the alloy band structure than the bond-centered CPA used by Chen and Sher.

As pointed out in last year's comprehensive proposal, the MCPA is suitable for treating both atomic and chemical disorder in pseudobinary alloys such as Ga(In, As). Its use was motivated in the present case by the experimental observation that in this alloy the GaAs distances and the InAs distances correspond closely to those encountered in the pure crystal, but that the average lattice constant, as determined for example by x-ray measurements, closely follows Vegard's Law. In addition to the combined effects of chemical and structural disorder on electronic structure, Ehrenreich and Hirth [2] have also explained the experimentally observed dislocation reduction in GaAs upon the addition of small amounts of In using a classical strain model. The work pertaining to charge dislocations and jogs in HgCdTe described in last year's proposal has been completed and published [3].

References:

1. R. Lempert, "Electric Theory of Semiconducting III-V and II-VI Alloys," Ph.D. Thesis, Harvard University, Division of Applied Sciences, 1985.

2. H. Ehrenreich and J.P. Hirth, "Mechanism for Dislocation Density Reduction in GaAs Crystals by Indium Addition," *Appl. Phys. Lett.* **46**, 7, 668 (1985).

3. J.P. Hirth and H. Ehrenreich, "Charged Dislocations and Jogs in $Hg_{1-x}Cd_xTe$ and Other II-VI Compounds," *J. Vac. Sci. Technol.* **A3**, 2, 367 (1985).

I.4 Electronic Structure of HgCdTe and Related Non-Magnetic II-VI Alloys: HgZnTe, CdZnTe. K.C. Hass, Contract N00014-84-K-0465; Research Unit 1.

K.C. Hass is investigating the stability of ordered 50-50 alloys of these materials having the chalcopyrite structure and the corresponding disordered case. This investigation is important because the influence of Cd d-levels on the cohesive energy is significant and is not yet understood. Furthermore, it permits an investigation of the possible importance of short-range order among the constituents as contrasted to possible segregation. It may be, for example, that the 50-50 alloy is less stable than the phase separated mixture. Charge transfer effects which are important because they stabilize the cohesive energy can be investigated. These transfers have marked effects on electronic levels and influence band offsets, which are of particular importance in heterojunctions. Finally, these calculations serve as another input to the parameterized alloy calculations described above.

I.5 Chemical Trends in Diluted Magnetic Semiconductors. H. Ehrenreich, B. Larson, and K.C. Hass, Contract N00014-84-K-0465; Research Unit 1.

We are also investigating the chemical trends in the family of materials characterized by CdMnTe and ZnMnTe with Se and S substituted for the chalcogenide. We have been able to explore the variation of the position of the d-levels and the strength of the sp-d hybridization by utilizing simple but rather generally applicable results obtained from detailed calculations for CdMnTe. The same applies to the magnitude of exchange interactions, which are also under investigation.

I.6 Amorphous Semiconductors. H. Ehrenreich and K.C. Hass, Contract N00014-84-K-0465; Research Unit 1.

Sum rules involving the dielectric function weighted by various powers of the frequency have been utilized to analyze the differences between chemical bonding in amorphous materials and their crystalline counterparts [1]. They are seen to provide fairly direct information concerning the short-range order present in amorphous semiconductors. They should therefore be useful as a method of experimental investigation of such effects. The so-called independent band model for amorphous semiconductors, which supposes that the valence and conduction bands are independent of each other is frequently invoked in the interpretation of the optical fundamental absorption edge. Tauc's law is based on, and Urbach Tails have been explained using this model.

Reference:

1. K.C. Hass and H. Ehrenreich, "Electronic Structure Models, Bonding and Optical Moments in Amorphous and Crystalline Semiconductors," *Annals of Physics* **164**, 77 (1985).

I.7 Photovoltaics. H. Ehrenreich, Contract N00014-84-K-0465; Research Unit 1.

Ehrenreich's interest in an involvement with photovoltaics continues, albeit on a somewhat reduced level. Last March he was asked to testify before the House Committee on Science and Technology chaired by Congressman Don Fuqua concerning the FY'86 budget for photovoltaics [1].

Reference:

1. H. Ehrenreich, "Hearings before the Subcommittee on Energy Developments and Applications of the Committee on Science and Technology," U.S. House of Representatives, March 5, 1985, No. 31, Vol. III.

ANNUAL REPORT OF

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers Submitted to Refereed Journals (and not yet published)

K.C. Hass, B.E. Larson, H. Ehrenreich, and A.E. Carlsson, "Magnetic Interactions in Diluted Magnetic Semiconductors," accepted for publication in *J. Magnetism and Magnetic Materials* (Proceeding of the Int. Conf. on Magnetism, 1985).

B.E. Larson, K.C. Hass, and R.L. Aggarwal, "Effects of Internal Exchange Fields on Magnetization Steps in Diluted Magnetic Semiconductors," accepted for publication in *Phys. Rev.* **B.**

b. Papers Published in Refereed Journals

H. Ehrenreich and J.P. Hirth, "Mechanism for Dislocation Density Reduction in GaAs Crystals by Iridium Addition," *Appl. Phys. Lett.* **46**, 7, 668 (1985).

B.E. Larson, K.C. Hass, H. Ehrenreich, and A.E. Carlsson, "Exchange Mechanisms in Diluted Magnetic Semiconductors," *Solid State Commun.* **56**, 4, 347 (1985).

J.P. Hirth and H. Ehrenreich, "Charged Dislocations and Jogs in $Hg_{1-x}Cd_xTe$ and Other II-VI Compounds," *J. Vac. Sci. Technol.* **A3**, 2, 367 (1985).

K.C. Hass and H. Ehrenreich, "Electronic Structure Models, Bonding and Optical Moments in Amorphous and Crystalline Semiconductors," *Annals of Physics* **164**, 77 (1985).

H. Ehrenreich, "Hearings before the Subcommittee on Energy Developments and Applications of Committee on Science and Technology," U.S. House of Representatives, March 5, 1985, No. 31, Vol. III.

c. Books (and sections thereof) Submitted for Publication

H. Ehrenreich and D. Turnbull, eds., *Solid State Physics*, Volume 39, Academic Press.

d. Books (and sections thereof) Published

H. Ehrenreich and D. Turnbull, eds., *Solid State Physics*, Volume 38, Academic Press, 1984.

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

B.E. Larson, K.C. Hass, and R.L. Aggarwal, "Magnetic Interactions in Diluted Magnetic Semiconductors," International Conference on Magnetism (San Francisco, August 1985).

K.C. Hass and H. Ehrenreich, "Implications of Optical Moment Comparisons of Amorphous and Crystalline Semiconductors", American Physical Society (Baltimore, March 1985).

K.C. Hass, B.E. Larson, H. Ehrenreich, and A.E. Carlsson, "Electronic Structure and $sp-d$ Exchange in Semimagnetic Semiconductors", American Physical Society (Baltimore, March 1985).

i. Honors/Awards/Prizes

H. Ehrenreich, Visiting Exchange Scholars Program with People's Republic of China, National Academy of Science, May 1985.

R. Lempert, "Electronic Theory of Semiconducting III-V and II-VI Alloys," Ph.D. Thesis, Harvard University, Division of Applied Sciences, 1985.

K.C. Hass, "Topics in Electronic Theory of Disordered Semiconductors", Ph.D. Thesis, Harvard University, Division of Applied Sciences, October 1984.

I.8 Investigation of Amorphous Hydrogenated and Fluorinated Alloys of Silicon and Germanium. J. Hanna, K.D. Mackenzie, Z.L. Sun, J.H. Burnett, J.R. Eggert, Y.M. Li, and W. Paul, Contracts N00014-84-K-0465 and SERI Subcontract XB-2-02144-1 of DOE Prime Contract DE-AC-02-83-CH10093; Research Unit 2.

In the previous report (No. 98), we discussed our conclusions regarding the properties of amorphous hydrogenated alloys of silicon and germanium ($a\text{–}Si_{1-x}Ge_x$: H). These alloys have a smaller band-gap than a-Si: H, which makes them useful for electrophotographic materials with improved "red" response and also for the lower-band-gap component of tandem solar cells. From the fundamental point of view, the amorphous group 4-group 4 alloys may be looked upon as prototypes for many compound amorphous semiconductors of the silicon family. A characteristic of these 4-4 (or 3-5 etc.) alloys is that their photoelectronic properties are inferior to those of a-Si: H, for reasons that are not yet understood. We had earlier investigated $a\text{–}Si_{1-x}Ge_x$: H produced by diode sputtering and d.c. glow discharge, and this was followed up with a detailed study of alloys prepared by the more conventional technique of r.f. glow discharge. Based on a systematic examination of the structural, optical and transport properties of samples prepared under a variety of deposition conditions, we have published our conclusions regarding their atomic structure and electronic band structure [1]. One of these conclusions concerned an inferred looser, more defected atomic structure in the Si-Ge alloys than in Si itself.

Several years ago, the Principal Investigator suggested [2] that improvements in the properties of Si-Ge alloys might eventuate if a different bond terminator than H were used. The bond terminator, F, had already been proposed and investigated by the group at ECD [3]. This suggestion was taken up by a Japanese group [4] which determined deposition conditions for $a\text{–}Si_{1-x}Ge_x$: H: F leading to much improved photoconductive response. We have now completed the first phase of an investigation of amorphous alloys of $Si_{1-x}Ge_x$ by the glow

discharge decomposition of mixtures of SiF_4, GeF_4 and H_2 and have presented our findings [5]. In brief, they confirm the result of the Japanese group that the photoconductivity may be improved by about an order-of-magnitude, while they show that in every other respect (conductivity, optical absorption edge spectrum, vibrational absorption spectrum, photoluminescence) there is no essential difference between a–$Si_{1-x}Ge_x$: H prepared from hydrides and a–$Si_{1-x}Ge_x$: H: F prepared from fluorine-containing gases.

The investigation of a–$Si_{1-x}Ge_x$: H: F from mixtures of SiF_4, GeF_4 and H_2 was carried out on samples prepared at different substrate temperatures, with different SiF_4: GeF_4 gas pressures and flow rates, and at different r.f. power levels. Optimum parameters were chosen, with a focus on the properties of samples with an energy gap in the 1.4-1.5 eV range. A wide variety of properties were then measured (vibrational absorption, optical absorption edge, conductivity versus temperature, photoconductivity magnitude, photoconductivity spectra, *photoluminescence*). Although minor differences were found in many of these properties from those measured on alloys prepared from hydrides, the most striking and consistent change was an order-of-magnitude increase in the photoconductivity.

Several points, however, were notable. First, the content of F was of the order of 1 atomic percent, while that of H was ten times larger; this suggested, rather obviously, that H was still the major element responsible for the compensation of dangling bonds. Second, the results of transmission electron microscopic measurements (TEM) on thin films of a-Si: H, a-Ge: H, a–$Si_{1-x}Ge_x$: H, a-Si: H: F, and a–$Si_{1-x}Ge_x$: H: F confirmed earlier indications that the morphology on a scale of 50-100 Å was quite likely different. Indeed, the different structures on this size scale of a-Si: H, a-Ge: H and a–$Si_{1-x}Ge_x$:H had been established much earlier by us [2], and all subsequent investigations by other laboratories known to us have confirmed our conclusions. The new element at this point is the finding that the

alloy a–$Si_{1-x}Ge_x$: H: F prepared from fluorine-containing gases appears less defected than the corresponding a–$Si_{1-x}Ge_x$: H prepared from the hydride. Our tentative model, is that the presence of F, or HF, or other F-containing molecules in the preparation plasma can lead to etching of the growth surface of the film, so that weakly-coordinated surface entities are removed, and a denser, less defected alloy structure is produced.

This research track postulates that a major contributory element to the inferior properties of $Si_{1-x}Ge_x$ alloys to those of Si itself lies in the structure on a 100 Å scale, and that explanations based on a different electronic band structure of a *homogeneous* disordered alloy will be found to be insufficient. As a result, we are dividing our present efforts between examinations directed at investigating the comparative gap-densities-of-states of the hydrogenated and hydro-fluorinated alloys and examinations directed toward elucidation of the microstructure. In the former category, we include (1) determination of the gap density-of-states near the Fermi level by the space-charge-limited current method, (2) determination of the gap density-of-states by interpretation of the low photon energy absorption spectrum from photoconductivity spectra, and (3) determination by the time-of-flight technique of dispersive transport and deep trapping time. In the latter category we are investigating (1) the gas evolution spectrum of a–$Si_{1-x}Ge_x$: H: F and its comparison with earlier spectra from a-Si: H, a-Ge: H and a–$Si_{1-x}Ge_x$: H, since different scale microstructure has usually been found in the past to correlate with different photoelectronic properties, and (2), in collaboration with the group of Professor R. Norberg of Washington University in St. Louis, the nuclear quadrupole resonance of deuterium in the different alloys [7]. This new and powerful technique (for these alloys) has the potential for examining the local surroundings and the dynamics of motion of D and D_2, and therefore for contributing significantly to our knowledge of the microstructure.

References:

1. K.D. Mackenzie, J.R. Eggert, D.J. Leopold, Y.M. Li, S. Lin, and W. Paul, *Phys. Rev.* **B31**, 2198 (1985).

2. W. Paul, in *Fundamental Physics of Amorphous Semiconductors*, Vol. 25 of Springer Series in Solid State Sciences (Springer, Heidelberg, 1981), p. 72.

3. S.R. Ovshinsky and A. Madan, *Nature* **276**, 482 (1978).

4. K. Nozawa, Y. Yamaguchi, J. Hanna, and I. Shimizu, *J. Non-Cryst. Solids* **59-60**, 533 (1983).

5. K.D. Mackenzie, J. Hanna, J.R. Eggert, Y.M. Li, Z.L. Sun, and W. Paul, Proc. Int. Conference on Amorphous Semiconductors, Rome, 1985, to be published in *J. Non-Cryst. Solids.*

6. K.D. Mackenzie, Report at the Annual Chelsea Conference on Amorphous Semiconductors, London, December 1985.

7. R. Norberg and W. Paul, Proc. Int. Conference on Amorphous Semiconductors, Rome, 1985, to be published in *J. Non-Cryst. Solids.*

I.9 Investigation of Neutron Transmutation Doping of a-Si: H. J.H. Burnett, Z.L. Sun, K.D. Mackenzie, Y.M. Li, J.R. Eggert, and W. Paul, Contract N00014-84-K-0465; Research Unit 2.

Neutron transmutation doping (NTD) has been demonstrated to be effective in achieving accurate, uniform phosphorus doping in crystalline silicon. The question arises whether the technique can be effective for phosphorus-doping hydrogenated amorphous silicon and offer advantages over gas phase and ion implantation doping. Hamanaka et al. [1] have reported that NTD is effective in this way, however, since the results seemed to us to be inconclusive, we have undertaken a re-examination of this possibility.

Since the neutron irradiation causes extensive damage, very careful anneal studies of the neutron-irradiated films must be carried out. These were done in parallel with anneal studies of undoped and unirradiated, and of light, intermediate and heavy gas-phase *P* doping. The conductivity, conductivity activation

energy, and photoconductivity of the different films where studied after anneal times up to 30 hours at 230 ° C, which was also the film deposition temperature.

Based on a detailed comparison of the long-time anneal-stable transport and photo-transport, we have concluded that the NTD technique is unsuitable for use in a-Si: H technology. At short times there do exist large shifts in the Fermi level which simulate the effect of considerable *P*-doping, but these are related to defects and are not stable. This study also showed that even in gas-phase *P*-doped a-Si:H there exists much annealable damage, which calls into question the present view of "doping efficiency" for a-Si: H. The conclusions of this study were presented at the Rome Conference on Amorphous Semiconductors [2]. There remain to be done other measurements to consolidate the statistics of our results before a conclusive report is published.

References:

1. H. Hamanaka, K. Kuriyama, M. Yahagi, M. Satoh, K. Iwamura, C. Kim, Y. Kim, F. Shiraishi, K. Tsuji, and S. Minomura, *Appl. Phys. Lett.* **45**, 786 (1984).

2. J.H. Burnett, Z.L. Sun, K.D. Mackenzie, Y.M. Li, J.R. Eggert, and W. Paul, Proc. of the Rome Conference on Amorphous Semiconductors, 1985, to be published in *J. Non-Cryst. Solids.*

I.10 Metastable Semiconducting Alloys of $Ge_{1-x}Sn_x$. S. Lee, J.H. Burnett, and W. Paul, Contract N00014-84-K-0465; Research Unit 2.

Films of amorphous $Ge_{1-x}Sn_x$ were prepared by r.f. sputtering of composite crystalline targets for nine values of x between 0 and 0.4. The substrate temperature was kept low by circulating water at room temperature. The composition of the amorphous films, all about 10 microns thick, was determined by electron microprobe.

At first the films were removed from the substrate by simply scraping them off. Subsequent runs in a differential scanning calorimeter showed one peak only (see below). A second run in the same sample indicated a feature at 232 ° C clearly identified with the melting of β–Sn. It was therefore inferred that at least some of the material scraped off the substrate was, in fact, microcrystalline $Ge_{1-x}Sn_x$. Other methods of preparing a free-standing film were sought.

The technique adopted involved depositing the Ge-Sn alloy onto polyimide film coating a microscope glass slide, and later floating the film free by dissolving the polyimide in methylene chloride. The largest pieces of film so produced were about 5 mms in diameter, satisfactorily large enough for electrical and optical measurements.

All of these films were annealed in a differential scanning calorimeter (DSC) to approximately 550 ° C. For all values of $x > 0$, two peaks were observed with temperature increase: one inferred to be caused by crystallization, and the second by phase separation. A second run on each film, increasing the temperature, gave a peak at 232 ° C, which clearly corresponded to the melting temperature of β–Sn.

The temperature of the first (crystallization) peak varied linearly with x from a value of 500 ° C for $x = 0$ to an (extrapolated) value of 25 ° C for $x = 0.5$. The temperature intervals between the crystallization and phase separation peaks in the DSC did not depend on x, but appeared to vary with the heating rate in the calorimeter. More work on this dependence is required and is planned.

The actual interval varied between 20 ° C and 100 ° C. From this result it seems likely that it will be possible to anneal the film to an intermediate temperature, where phase separation has not proceeded very far. This is precisely the regime sought by our experiments.

ANNUAL REPORT OF

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers Submitted to Refereed Journals (and not yet published)

K.D. Mackenzie, J. Hanna, J.R. Eggert, Y.M. Li, Z.L. Sun, and W. Paul, Proc. International Conference on Amorphous Semiconductors, Rome, 1985, to be published in *J. Non-Cryst. Solids.*

K.D. Mackenzie, Report at the Annual Chelsea Conference on Amorphous Semiconductors, London, December 1985.

J.H. Burnett, Z.L. Sun, K.D. Mackenzie, Y.M. Li, J.R. Eggert, and W. Paul, Proc. International Conference on Amorphous Semiconductors, Rome, 1985, to be published in *J. Non-Cryst. Solids.*

I.11 X-Ray Scattering from Liquid and Solid Surfaces. A. Braslau, D. Schwartz, B. Ocko, I. Tidswell, G. Swisslow, and P.S. Pershan, Contracts N00014-84-K-0465, NSF DMR-82-12189 and NSF Travel Grant INT-83-11841; Research Unit 3.

We have been able to improve the operation of the liquid surface spectrometer that is installed on the Harvard MRL Rotating-Anode Facility such that for some experiments the signal-to-background is within one order-of-magnitude of the signal-to-background that has been obtainable at the German synchrotron facility HASYLAB. This was achieved by repositioning certain slits, relative to the monochromator, in such a way as to make the mechanical alignment simpler. This had the effect that one could use a wider vertical slit (coarser transverse out of plane resolution) and thereby increase the incident intensity. Although this is a considerable improvement for study of surface roughness on simple liquids it is not appropriate for study of the smectic-like order at liquid crystal surfaces since the latter require higher resolution, and therefore narrower slits.

As a result we have been able to do much more in the way of sample control and development then we could when we were limited to only a limited number of synchrotron measurement periods in any given year. For example, at the close of the last report period we had made preliminary synchrotron measurements on one sample of the AOT-oil-water microemulsion system that demonstrated some structure along the normal to the surface [1].

We have now repeated that measurement with a new sample on the Harvard facility and also looked at a second sample of different concentration. On the basis of both the repeatability and the systematics we now believe that the observed structure is not any sort of artifact and in the next report period we plan to perform a more complete set of measurements and to also develop mathematical models for the surface properties.

We are continuing our studies of the surface roughness of solid surfaces. We have been able to identify a number of empirical phenomena that are directly related to the surface roughness and we are in the process of trying to develop theoretical models to explain the data. In collaboration with the Harvard MRL program (Prof. G. Whitesides of Chemistry) we have also started to investigate the effects of organic monolayer coatings on selected solid substrates. These coatings have the potential advantage that chemical techniques can be used to engineer coatings with diverse properties. People working on these types of coatings have been hampered by the lack of good diagnostic methods to evaluate the chemically produced surfaces. We believe that x-ray reflectivity is an ideal method for this purpose.

Finally, we have designed a surface spectrometer that will be constructed on beam line 22B on the x-ray ring at the National Synchrotron Light Source at Brookhaven National Laboratories. The Harvard contribution to capital equipment costs for this spectrometer are being supported by the National Science

Foundation through the Harvard Materials Research Laboratory. Travel costs incurred by Prof. Pershan in developing the spectrometer are partially supported by the JSEP program and the NSF under a separate grant to Prof. Pershan. We anticipate that in future years all of the liquid surface synchrotron studies supported by the JSEP grant will be done using this spectrometer and that use of the German facility HASYLAB will be phased out.

Reference:

1. M. Kotlarchyk, S-H. Chen, J.S. Huang, and M.W. Kim, *Phys. Rev. Lett.* **53**, 941 (1984).

I.12 Light Scattering from Thin Smectic Films. S. Amador, Contracts N00014-84-K-0465 and NSF DMR-82-12189; Research Unit 3.

Data collection on the light scattering experiment is at the end of the learning curve and yielding results. Problems in sample purity and data analysis and taking have been resolved, and data on DOBAMP is available for temperatures deep in the SmC regime. Films are now stable into the transition regions, so that critical measurements can be made at both the SmC-SmA and the SmI-SmC transitions. It was decided to do the SmI-SmC transition first because of speculation that surface SmI phase might form before the actual bulk transition. New interest in this technique came about when synchrotron x-ray measurements [1] revealed the presence of a hexatic phase on the surface of a free-standing film of 70.7 at temperatures where the interior has the bulk Sm-C phase. Since both these phases are birefringent, the possibility exists of measuring pretransitional effects in this surface phase using light scattering.

Several problems were overcome in the course of these measurements. The laser, a Spectra Physics helium neon laser, experienced problems due to aging vacuum tubes and a bad plasma tube. These maintenance problems have been remedied.

In the past year, the light scattering experiment has been fully automated so that measurements can be made through semi-autonomous scans. Data from the experiment can now be transferred from the dedicated IBM personal computer to the group's more powerful PDP11/73 for data analysis and viewing. This necessitated bringing up KERMIT, a communications program, on both computers, and writing macros to enable use of standard plotting and fitting routines. It also involved the purchase of an additional communications board for the IBM to enable data transfer. In addition, the minicomputer was a recent acquisition and required an investment of time in learning to use it and its unfamiliar operating system. Programs to compensate for experimental errors are almost complete also.

Reference:

E.B. Sirota, P.S. Pershan, S. Amador, and L.B. Sorensen, "X-Ray Observation of a Single Hexatic Layer on the Surface of a Smectic-C Liquid Crystal Film," to be submitted to *Phys. Rev. Lett.*.

ANNUAL REPORT OF

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers Submitted to Refereed Journals (and not yet publised)

E.B. Sirota, P.S. Pershan, S. Amador, and L.B. Sorensen, "X-Ray Observation of a Single Hexatic Layer on the Surface of a Smectic-C Liquid Crystal Film," to be published.

b. Papers Published in Refereed Journals

A. Braslau, M. Deutsch, P.S. Pershan, A.H. Weiss, J. Als-Nielsen, and J. Bohr, "Surface Roughness of Water Measured by X-Ray Reflectivity," *Phys. Rev. Lett.* **54**, 114 (1985).

I.13 Chaos in Driven Josephson Junctions. Qing Hu, M. Iansiti, J.U. Free, and M. Tinkham, Contracts N00014-83-K-0383 and N00014-84-K-0465; Research Unit 4.

When a nonlinear device such as a Josephson junction is driven periodically at a sufficient amplitude, the response may cease to be periodic, and acquire a noisy, aperiodic time-dependence, referred to as "chaos." Since Josephson mixers must be driven into the strongly nonlinear regime to be efficient, it is a matter of practical concern that other parameters be chosen so as to avoid stumbling into a chaotic regime, with its extremely poor signal-to-noise ratio. To be able to avoid this problem in design, one must understand the numerous routes to chaos which a given system may display, at least well enough to avoid them. On the other hand, the study of these chaotic phenomena is currently a forefront area of research because of the insight offered by model systems into the generation of random noise from a noiseless drive in deterministic systems.

During the current period, we have extended [1] the preliminary observations and simulations reported earlier. The junctions studied were Nb-aSi-Nb SNAP junctions, fabricated by the Sperry Lab. in Sudbury before it closed, and supplied to us by Dr. L.N. Smith. These junctions are robust enough to be studied over a long period of time without change of parameter values, and of low enough resistance relative to the antenna impedance that they can be modeled as current-driven at submillimeter wave frequencies. (Voltage driven high R junctions do not show chaos, but they suffer from noise-rounded characteristics.) Since the plasma frequency of these junctions is about 400 GHz, our limited FIR (far-infrared) laser power is most effective in driving them into the chaotic regime when a laser line near that frequency is used.

We have compared our I-V curve data taken at a range of FIR laser power levels with detailed simulations, based on the RSJ model extended to take account of the marked change in quasiparticle conductance at the energy-gap voltage. In

this way, we have identified two distinct chaotic regimes. In the more common of the two, the motion is characterized by a "strange attractor," i.e., even in the absence of any noise input, the driven deterministic motion is not periodic, but shows a noisy chaotic variation from cycle to cycle. However, we have also identified chaotic motion in a parameter range where the noiseless equations of motion lead to one of two strictly periodic solutions, corresponding to the zeroth or the 2/3 Josephson step, respectively. The range of initial conditions leading to each of these periodic motions is described as the "basin of attraction" for that motion. In this case, these basins are extremely finely intertwined, being separated by a basin boundary of fractal dimension larger than 1 and as high as 1.85. As pointed out by Grebogi, McDonald, Ott, and Yorke [2], this fractal dimension is a measure of how sensitive these periodic solutions are to being interrupted by small amounts of noise input, since as the dimension approaches 2, the boundary fills the entire phase plane. Our experimental data confirm this qualitative relationship, the dependence on dc bias current of the measured low-frequency noise power being very similar to the dependence on i_{dc} of the fractal dimension. To the best of our knowledge, this is the first direct confirmation of this plausible theoretical prediction. Moreover, our simulations show for the first time that the amount of noise required to convert the periodic solution to a chaotic one, switching intermittently between the two steps, is small enough to be supplied by the electronic shot noise of the quasiparticle current in the junction, even if the device were free of all thermal or extrinsic noise. In addition, the simulations show that the absolute noise levels resulting from these two very different types of chaos should be similar, as is observed experimentally.

Because the experimental noise observations are made at audio frequencies 10^9 times lower than the FIR drive frequency at which the chaotic motion occurs. the frequency spectrum of the noise is critical to a quantitative comparison of

simulation and experiment. Our preliminary low-frequency noise-spectrum data show inverse-frequency dependences ranging from f^{-1} to f^{-4} depending on bias conditions. A systematic study of these dependences is now underway.

References:

1. M. Iansiti, Qing Hu, R.M. Westervelt, and M. Tinkham, *Phys. Rev. Lett.* **55**, 746 (1985).

2. C. Grebogi, S.W. McDonald, E. Ott, and J.A. Yorke, *Phys. Lett.* **99A**, 415 (1983).

ANNUAL REPORT OF

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers Submitted to Refereed Journals (and not yet published)

H. Akoh, O. Liengme, M. Iansiti, M. Tinkham, and J.U. Free, "Reentrant Temperature Dependence of Critical Current in Small Tunnel Junctions," submitted to *Phys. Rev.*.

b. Papers Published in Refereed Journals

J. Bindslev Hansen, M. Tinkham, and M. Octavio, "Subharmonic Energy Gap Structure and Excess Current in Niobium Point Contacts," Proc. LT-17 Conf., Karlsruhe, W. Germany, August 1984, North Holland Press, 435-436 (1984).

W.C. Danchi, J. Bindslev Hansen, M. Octavio, F. Habbal, and M. Tinkham, "Effects of Noise on the dc and Far-Infrared Josephson Effect in Small-Area Superconducting Tunnel Junctions," *Phys. Rev.* **B30**, 2503-2516 (1984).

W.C. Danchi, F. Habbal, J.U. Free, M. Tinkham, and L.N. Smith, "Response of Nb-aSi-Nb Junctions to 604 GHz Radiation," Proc. 1984 Appl. Supercon. Conf., San Diego; *IEEE Trans. Mag.* **MAG-21**, 219-222 (1985).

Qing Hu, J.U. Free, M. Iansiti, O. Liengme, and M. Tinkham, "Chaotic Behavior Observed in a dc-Biased Josephson Junction Driven at FIR Frequencies," Proc. 1984 App. Supercond. Conf., San Diego; *IEEE Trans. Mag.* **MAG-21**, 590-593 (1985).

M. Iansiti, Qing Hu, R.M. Westervelt, and M. Tinkham, "Noise and Chaos in a Fractal Basic Boundary Regime of a Josephson Junction," *Phys. Rev. Lett.* **55**, 746-749 (1985).

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

M. Tinkham, "Small-Area Josephson Devices for Submillimeter Wavelengths," Invited Paper at US-Japan Workshop on Josephson Electronics, Kauai, Hawaii, June, 1985.

I.14 Nonlinear Dynamics of Small Neural Networks with Finite Frequency Response. K. Babcock and R.M. Westervelt, Contract N00014-84-K-0465; Research Unit 5.

We are investigating the nonlinear dynamics of networks of electrical threshold switching elements which mimic biological neural networks. These show considerable promise for rapid pattern recognition and optimization problems; however, their dynamics resemble those of a spin glass and are only poorly understood. Most work to date has focussed on algorithms to produce multiple steady states in simulations of large networks. Serious performance problems may occur in real networks where the switching elements have finite frequency response, including the appearance of unwanted collective modes produced by phase shifts in real elements, and exceptional sensitivity to noise produced by complex basin boundaries [1]. The significance of these problems can be appreciated by the difficulty of operating a conventional digital computer without a synchronizing clock.

We have investigated the dynamics of relative simple networks, using mathematical analysis, computer simulations, and experiments on circuits composed of integrated circuit amplifiers [2]. Our goal has been to understand the nonlinear dynamics of small systems with 2 to 4 nodes (and 4 to 16 degrees of freedom) in some detail, in order to identify simple characteristic phenomena

which can be used to analyze the behavior of larger networks with greater potential computational power, but hopelessly complex dynamics.

In a network with two switching elements and two steady states, we find rapid convergence to the steady states, and a smooth boundary separating their basins of attraction only if the frequency response of the elements is assumed to be infinitely fast. When a more realistic model including phase shifts in each element is used, the response of the network is much more complex. The transient response displays damped ringing even when the interconnection matrix T_{ij} is symmetric, and the response to periodic excitation becomes irregular and chaotic in certain cases when the drive frequency is near the high frequency cut off of the elements. Under these circumstances one also expects that the boundaries of the basins of attraction for the two steady states are highly folded fractal sets which cause extraordinary sensitivity to the choice of initial conditions; this issue is currently under investigation. A small-signal analysis defines potentially troublesome combinations of operating parameters and provides a means for avoiding irregular response.

References:

1. E.G. Gwinn and R.M. Westervelt, "Intermittent Chaos and Low Frequency Noise in the Driven Damped Pendulum," *Phys. Rev. Lett.* **54**, 1613 (1985).

2. K. Babcock and R.M. Westervelt, "Nonlinear Dynamics of Small Neural Networks with Finite Frequency Response," to appear.

ANNUAL REPORT OF

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

This is a new research unit. The following publications report related work supported by ONR Contract N00014-84-K-0329.

a. Papers Submitted to Refereed Journals (and not yet published)

S.W. Teitsworth and R.M. Westervelt, "Deterministic Noise in Extrinsic Photoconductors," Proc. 8th Int. Conf. on Noise in Physical Systems, Rome, 9-13 Sept. 1985, in press.

S.W. Teitsworth and R.M. Westervelt, "Subharmonic and Chaotic Response of Periodically-Driven Extrinsic Ge Photoconductors, submitted to *Phys Rev. Lett.*

E.G. Gwinn and R.M. Westervelt, "Fractal Basin Boundaries and Intermittency in the Driven Damped Pendulum," submitted to *Phys Rev.* **A**.

b. Papers Published in Refereed Journals

E.G. Gwinn and R.M. Westervelt, "Intermittency and Low Frequency Noise in the Damped Driven Pendulum," in Proc. 17th Int. Conf. on Low Temperature Physics, Karlsruhe, W. Germany, U. Eckern, A. Schmid, W. Weber and H. Wuhl, eds., (North-Holland, Amsterdam, 1984), p. 1139.

S.W. Teitsworth and R.M. Westervelt, "Chaos and Broadband Noise in Extrinsic Photoconductors," *Phys. Rev. Lett.* **53**, 2587 (1984).

R.M. Westervelt and S.W. Teitsworth, "Nonlinear Transient Response of Extrinsic Ge Far-Infrared Photoconductors," *J. Appl. Phys.* **57**, 5457 (1985).

E.G. Gwinn and R.M. Westervelt, "Intermittent Chaos and Low Frequency Noise in the Driven Damped Pendulum," *Phys. Rev. Lett.* **54**, 1613 (1985).

c. Books (and sections thereof) Submitted for Publication

R.M. Westervelt, S.W. Teitsworth, and E.G. Gwinn, "Nonlinear Dynamics in Semiconductors, Intermittency, and Low Frequency," in *Perspectives in Nonlinear Dynamics* (World Scientific Publishers, Singapore, 1986), in press.

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

R.M. Westervelt, "Chaos in Semiconductors and in Josephson Junctions," Université de Sherbrooke, Regional School of Physics, 29-31 October, 1984.

R.M. Westervelt, "Nonlinear Dynamics and Chaos in Extrinsic Photoconductors," American Physical Society, Symposium on the Physics of Infrared Detectors (Baltimore, March 25, 1985).

R.M. Westervelt, "Nonlinear Dynamics in Semiconductors," Perspectives in Nonlinear Dynamics, Office of Naval Research Workshop, 28-30 June, 1985.

II. QUANTUM ELECTRONICS

Personnel

Prof. N. Bloembergen
Asst. Prof. E. Mazur
Assoc. Prof. T.W. Mossberg
Dr. C.Y. Huang
Dr. A.M. Malvezzi
Dr. Y.H. Zou
Mr. W.R. Babbitt
Mr. Y.S. Bai
Mr. K.H. Chen
Mr. J. Eggert
Mr. J.E. Golub
Mr. J. W[illegible]g
Mr. A.G. Yodh

II.1 Experimental Studies of Photon Echo Pulse Compression. Y.S. Bai and T.W. Mossberg, Contracts N00014-84-K-0465 and ARO DAAG29-83-K-0040; Research Unit 6.

Following up on our previous theoretical work [1], we have performed an experimental study of the compression of frequency-chirped optical pulses using photon-echo-type effects [2]. We modified our cw ring dye laser so that we could generate long (hundreds of nanoseconds) pulses possessing a nearly linear frequency chirp. Photon echoes were generated by passing two frequency-chirped pulses through an oven containing vapor phase atomic Yb. When the chirp rate of the second laser pulse was adjusted to be twice that of the first, the duration of the echo signal was found to be given by the inverse of the total chirp bandwidth. Echoes having durations up to 30 times shorter than the first excitation pulse were observed. Moreover, the echo signal was found to contain up to 25% of the energy contained in the first laser excitation pulse. The present means of

compressing optical pulses is unique in that long input pulses can be compressed as well as short input pulses. Other techniques of optical pulse compression become difficult to employ when the input pulses are long.

References:

1. Y.S. Bai and T.W. Mossberg, "Photon Echo Optical Pulse Compression," *Appl. Phys. Lett.* **45**, 1269 (1984).

2. Y.S. Bai and T.W. Mossberg, "Experimental Studies of Photon-Echo Pulse Compression," *Opt. Lett.* (to be published, Jan. 1986).

II.2 Broad-Bandwidth Transient Four-Wave Mixing. J.E. Golub and T.W. Mossberg, Contracts N00014-84-K-0465 and NSF PHY-82-07080; Research Unit 6.

It was recently suggested [1] that transient nonlinear optical experiments employing broad-bandwidth laser pulses may be used to provide ultra-high temporal resolution in optical studies of material systems. In these experiments, the mixing signal is measured as a function of an optical delay introduced into the path of one of the input beams (at least two of which must be optically divided portions of the same laser output pulse). The mixing signal has been calculated to decay on the time scale of the longer of the laser coherence time or the transverse relaxation time of the material employed. The *overall* laser pulse duration is not important unless the optical delay becomes comparable to it. As a result, measurements of material relaxation rates should be limited only by the coherence time of the laser pulse employed.

We have conducted an experiment [2] in a simple collisionally perturbed gas-phase system designed to test the ideas described above. A 10-nanosecond dye laser pulse with a 1-10 nm bandwidth was optically split into three parts and used to generate a four-wave mixing signal in atomic sodium vapor. By using high argon perturber pressures (1-4 atmospheres) we were able to introduce collisional

decay times of 10-30 picoseconds. We found that the four-wave mixing signal decayed exponentially as a function of optical decay, and that the picosecond decay constant agreed beautifully with the collisional decay rate expected on the basis of traditional collision-broadening-type experiments. Our experiment, performed in a well understood material system, is essentially the first to show that broad-bandwidth transient mixing techniques can indeed provide reliable measurements of ultra-high speed relaxation processes.

References:

1. S. Asaka, H. Nakatsuka, M. Fujiwara, and M. Matsuoka, *Phys. Rev.* **A29**, 2286 (1984); N. Morita and T. Yajima, *Phys. Rev.* **30**, 2525 (1984).

2. J.E. Golub and T.W. Mossberg, "Studies of Picosecond Collisional Dephasing in Atomic Sodium Vapor Using Broad-Bandwidth Transient Four-Wave Mixing," submitted to the *J. Opt. Soc.* **B**.

II.3 Interaction of Atoms with Amplitude- and Phase-Controlled Optical Radiation. Y.S. Bai, A.G. Yodh, and T.W. Mossberg. Contracts N00014-84-K-0465 and ONR N00014-85-K-0724; Research Unit 6.

Although the behavior of two-level atoms exposed to nearly resonant laser light can be simply calculated in the semiclassical approximation and is generally assumed to be well understood, no experiments have been performed to date to actually observe the response of such atoms under conditions in which the atom-laser relative phase is important. In typical steady-state experiments, of which there are many, the observed signal depends on the ensemble averaged behavior of atoms with a wide range of phases relative to the applied field. In transient experiments, the laser's phase is generally held constant.

We have begun a series of experiments designed to probe the behavior of atoms responding to laser fields of well-specified phase [1]. These experiments are carried out in dilute atomic beams of atomic Yb. When excited by circularly

polarized 555.6 nm light, this atom constitutes an ideal two-level system. In our experiments, atoms initially in the ground state are excited by a gated cw laser field having a controllable phase. We monitor the atoms behavior by observing fluorescence emitted at right angles to both the atomic and laser beams.

In initial experiments [2], we have studied the behavior of atoms that are first exposed to a pulse of area $\pi/2$ (i.e., they are placed in an equal admixture superposition of ground and excited states) and then exposed to a laser field shifted in phase by 90 degrees with respect to the initial field. We have pointed out that this excitation process places the combined atom-laser field system into a stationary state. In resonance fluorescence theory, these states are called "dressed states." We have also pointed out that the resonance fluorescence spectrum characteristic of atoms excited to particular dressed states will be qualitatively different from that normally observed in steady-state experiments. We have demonstrated that atoms in dressed states do not exchange energy with the excitation field.

These experiments probe basic aspects of the interaction of simple atomic systems with laser radiation.

References:

1. Y.S. Bai, A.G. Yodh, and T.W. Mossberg, "Resonance Fluorescence During Phase-Controlled Transient Excitation," *Phys. Lett.* **111A**, 291 (1985).

2. Y.S. Bai, A.G. Yodh, and T.W. Mossberg, "Selective Excitation of Dressed Atomic States by Use of Phase-Controlled Optical Fields," *Phys. Rev. Lett.* **55**, 1277 (1985).

II.4 Collisional Relaxation of the $^3P_1$ State of Atomic Yb. A.G. Yodh and T.W. Mossberg, Contracts N00014-84-K-0465 and NSF PHY-82-07080; Research Unit 6.

We have employed [1] coherent transient techniques to study the relaxation of the $^3P_1$ state of atomic Yb collisionally perturbed by helium and argon. Specifically, our measurements are sensitive to velocity and phase thermalization of the rank one (orientation) and rank two (alignment) multipole moments of the $^3P_1$ Zeeman manifold. We provided the first measurement of the total quantum mechanical cross-section for destruction of excited-state Zeeman coherences and the first complete mapping of the collisional velocity-change spectrum characteristic of the collisions.

Reference:

1. A.G. Yodh, J. Golub, and T.W. Mossberg, "Collisional Relaxation of Excited-State Zeeman Coherences in Atomic Ytterbium Vapor," *Phys. Rev.* **A32**, 844 (1985).

II.5 Mixed Binary Multiplication Using Real-Time Optical Convolution. W.R. Babbit and T.W. Mossberg, Contracts N00014-84-K-0465 and ARO DAAG29-83-K-0040; Research Unit 6.

Using the method of real-time optical convolution developed here previously [1], we have shown [2] that it is possible to perform nanosecond-time-scale mixed binary multiplication of serially encoded optical data. In this process, two or three numbers are digitally encoded as an optical pulse train and made to interact with a resonant inhomogeneously broadened optical absorber. The input pulses modify the absorption profile of the material to represent the product of their Fourier transforms. Subsequent coherent free decay signals emitted by the sample effectively reverse transform the stored information and hence evolve in time as the convolution or cross-correlation of the input pulses. Mixed binary multiplication occurs when two or more binary encoded signals are convolved. Our

experiments indicate that, in weakly relaxing materials, the mixed binary output signal obtained with the present technique should be about 0.5% as intense as the input signals. Inaccuracies in the output signals were investigated and ascribed to correctable imperfections in our experimental system. Harvard has applied for a patent on this process.

References:

1. Y.S. Bai, W.R. Babbitt, N.W. Carlson, and T.W. Mossberg, "Real-Time Optical Waveform Convolver/Cross Correlator," *Appl. Phys. Lett.* **45**, 714 (1984).

2. W.R. Babbitt and T.W. Mossberg, "Mixed Binary Multiplication of Optical Signals by Means of Convolution in an Inhomogeneously Broadened Absorber," submitted to *Appl. Opt.*

ANNUAL REPORT OF

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers Submitted to Refereed Journals (and not yet published)

J.E. Golub and T.W. Mossberg, "Studies of Picosecond Collisional Dephasing in Atomic Sodium Vapor Using Broad-Bandwidth Transient Four-Wave Mixing," submitted to *J. Opt. Soc. Amer.* **B.** (Partial support from NSF)

N. Lu, P.R. Berman, A.G. Yodh, Y.S. Bai, and T.W. Mossberg, "Transient Probe Spectra in Strongly Driven Atoms and their Dependence on Initial Atomic Conditions," submitted to *Phys. Rev.* **A.** (Partial support from ONR and NSF)

Y.S. Bai and T.W. Mossberg, "Experimental Studies of Photon-Echo Pulse Compression," to be published in *Opt. Lett.*, Jan. 1986. (Partial support from ARO)

W.R. Babbitt and T.W. Mossberg, "Mixed Binary Multiplication of Optical Signals by Means of Convolution in an Inhomogeneously Broadened Absorber," submitted to *Appl. Opt.* (Partial support from ARO)

b. Papers Published in Refereed Journals

N.W. Carlson, W.R. Babbitt, Y.S. Bai, and T.W. Mossberg, "Spectrally Ordered Zeeman Coherences and Optical Pulse-Shape Storage," *J. Opt. Soc.* **B2**, 908 (1985). (Partial support from ARO)

Y.S. Bai, A.G. Yodh, and T.W. Mossberg, "Selective Excitation of Dressed Atomic States by Use of Phase-Controlled Optical Fields," *Phys. Rev. Lett.* **55**, 1277 (1985).

Y.S. Bai, A.G. Yodh, and T.W. Mossberg, "Resonance Fluorescence During Phase-Controlled Transient Excitation," *Phys. Lett.* **111A**, 291 (1985). (Partial support from NSF)

A.G. Yodh, J. Golub, and T.W. Mossberg, "Collisional Relaxation of Excited-State Zeeman Coherences in Atomic Ytterbium Vapor," *Phys. Rev.* **A32**, 844 (1985). (Partial support from NSF)

A.G. Yodh, J. Golub, and T.W. Mossberg, "Colliding Without Relaxing: The Suppression of Collisional Dephasing with Strong Optical Fields," in *Laser Spectroscopy VII*, T.W. Hansch and Y.R. Shen, eds., (Springer, Berlin, 1985). (Partial support from NSF)

Y.S. Bai, A.G. Yodh, and T.W. Mossberg, "Studies of Two-Level Atoms Identically Prepared by a Phase- and Amplitude-Controlled Excitation Field," in *Laser Spectroscopy VII*, T.W. Hansch and Y.R. Shen, eds., (Springer, Belin, 1985). (Partial support from NSF)

e. Patents Filed

T.W. Mossberg, W.R. Babbitt, Y.S. Bai, and N.W. Carlson, "Optical Cross-Correlation and Convolution."

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

J.E. Golub and T.W. Mossberg, "Terahertz Quantum Beat Spectroscopy," presented at the 1985 Gordon Conference on Lasers and Nonlinear Optics, August 1, 1985).

A.G. Yodh, Y.S. Bai, and T.W. Mossberg, "Studies of Two-Level Atoms Identically Prepared by Phase and Amplitude Controlled Excitation," presented at the 1985 Gordon Conference on Atomic Physics, July 1-5, 1985.

A.G. Yodh, J.E. Golub, and T.W. Mossberg, "The Collisional Relaxation of Excited-State Zeeman Coherences in Atomic Ytterbium Vapor," presented at the XIV International Conference on the Physics of Electronic and Atomic Collisions, Palo Alto, CA, July 23 - August 1, 1985.

Y.S. Bai and T.W. Mossberg, "Photon Echo Pulse Compression," presented at the 1985 Conference on Lasers and Electro-Optics (CLEO), May 22, 1985.

W.R. Babbitt, Y.S. Bai, N.W. Carlson, and T.W. Mossberg, "Spectral Holography and its Applications," presented at the 1985 Conference on Lasers and Electro-Optics, May 22, 1985.

Y.S. Bai, A.G. Yodh, T.W. Mossberg, N. Lu, and P.R. Berman, "Transient Excitation of Atoms Using Strong Phase-Controlled Laser Fields," presented at the 1985 Gordon Conference on Lasers and Electro-Optics, August 1, 1985.

Y.S. Bai, A.G. Yodh, and T.W. Mossberg, "Studies of Two-Level Atoms Identically Prepared by a Phase- and Amplitude-Controlled Excitation Field," presented at the Seventh International Conference on Laser Spectroscopy, Hawaii, June 24-28, 1985.

A.G. Yodh, J. Golub, and T.W. Mossberg, "Colliding Without Relaxing: The Suppression of Collisional Dephasing with Strong Optical Fields," presented at the Seventh International Conference on Laser Spectroscopy, Hawaii, June 24-28, 1985.

II.6 Nonlinear Four-Wave Mixing in Vapors. N. Bloembergen and Y.H. Zou, Contract N00014-84-K-0465; Research Unit 7.

During the past year a comprehensive experimental study of the collision-enhanced Hanle-type resonances in Na vapor with various buffer gases has been completed. After the original communication [1], referred to in the preceding annual report, the intensity and width of the zero magnetic field resonances in phase-conjugate degenerate-frequency four-wave light mixing have been systematically investigated as a function of several parameters. These include the pressure of the Ar and Xe buffer gas, the partial pressure of Na vapor, the detuning of the light frequency on both sides of the D_1 and D_2 sodium resonances and the intensity of the incident light beams. Power broadening and saturation effects have been observed and interpreted. It has been demonstrated theoretically that the collision-enhanced Hanle resonances are equivalent to the phenomenon of collision-induced transverse optical pumping. The relationship between the two

theoretical descriptions simply corresponds to a 90 degree rotation of the axis of spatial quantization. The detuning from resonance has been extended well over 100 GHz to about 600 GHz. In this regime the impact approximation is not valid and the line shape becomes asymmetrical. This is the regime of the quasi-static collisional deformation of the wave functions. All these effects are described in detail in a comprehensive paper, which has been submitted for publication [2].

Some preliminary experiments have been carried out on the collision-enhanced Hanle resonances in Samarium vapor. A new oven has been constructed which permits heating at 800 ° C to obtain sufficient vapor pressure of Sm atoms. This atom is of interest because it avoids the complications of the presence of hyperfine interaction present in Na. Furthermore, the near-resonant excited state is a single $(J = 0)$ state, while the ground state is a triply degenerate $(J = 1)$ state in zero magnetic field. The systematic variation of the states of polarization in the simple energy level scheme is of special interest. The Hanle resonance of the Sm atom with Ar and Xe buffer gases has been observed. A systematic investigation of the parametric dependences of the intensity and width of this Hanle-type signal is underway.

References:

1. N. Bloembergen, Y.H. Zou, and L.J. Rothberg, "Collision-Induced Hanle Resonances of Kilohertz Width in Phase-Conjugate Four-Wave Light Mixing," *Phys. Rev. Lett.* **54**, 186 (1985).

2. Y.H. Zou and N. Bloembergen, "Collision-Enhanced Hanle Resonances and Transverse Optical Pumping in Four-Wave Light Mixing in Na Vapor," submitted for publication in *Physical Review* **A**.

II.7 Picosecond Laser Interactions with Semiconductors. A.M. Malvezzi, C.Y. Huang, and N. Bloembergen, Contracts N00014-84-K-0465 and N00014-83-K-0030; Research Unit 7.

During this reporting period the experiments on the emission of neutral and charged particles from Si and GaAs were continued. For heating above the normal boiling point (or vaporization temperature), a regime of plasma formation is rapidly reached. When positive ions are extracted by applying a negative bias to the collecting electrode, a strong negative space-charge region is rapidly developed, which leads to further ionization in the vapor phase. Further theoretical studies of the emmission of positive ions are in progress.

Our technique of a picosecond pump heating pulse with subsequent probing of the changes in the optical complex index of refraction by picosecond probing pulses at several wavelengths with various time delays has been extended to graphite. A phase transition has been observed at a critical pump fluence of about 160 mJ/cm^2 at $\gamma = 0.53$ nm. An abrupt change in the reflectivity has been observed at several wavelengths, including $\gamma = 0.53\ \mu$m, 1.06 μm and 1.9 μm. The transition is tentatively identified with molten carbon. Since the reflectivity decreases, our results would indicate that the electronic structure of liquid carbon is not metallic, but rather molecular polymeric in nature. Further experimental and theoretical work on this problem is in progress.

Our pump and probe technique will also be used to investigate other high melting point refractory compounds, including silicon and tungsten carbide.

Several papers on these subjects [1-4] have been accepted for presentation at the Materials Research Society Symposium on Beam-Solid Interactions and Phase Transformations, held in Boston in December 1985. They will also be submitted for publication in the Proceedings of this symposium. A paper describing a simple model for the variation of the effective mass wih the electron-hole plasma density and temperature in silicon has been accepted for publication [5].

References:

1. N. Bloembergen, "Pulsed Laser Interactions with Condensed Matter."

2. J.M. Liu, A.M. Malvezzi, and N. Bloembergen, "Time-Resolved Optical Studies of Picosecond Laser Ineractions with GaAs Surfaces."

3. A.M. Malvezzi, C.Y. Huang, H. Kurz and N. Bloembergen, "Time-Resolved Spectroscopy of Plasma Resonances in Highly-Excited Silicon and Germanium."

4. C.Y. Huang, A.M. Malvezzi, and N. Bloembergen, "Time-Resolved Picosecond Optical Study of Laser-Excited Graphite."

5. G.Z. Yang and N. Bloembergen, "Effective Mass in Picosecond Laser-Produced High-Density Plasma in Silicon," acceped for Publication in *IEEE Journal of Quantum Electonics,* January 1986.

ANNUAL REPORT OF

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers Submitted to Refereed Journals (and not yet published)

Y.H. Zou and N. Bloembergen, "Collision-Enhanced Hanle Resonances and Transverse Optical Pumping in Four-Wave Light Mixing in Na Vapor," submitted for publication in *Physical Review* **A.**

G.Z. Yang and N. Bloembergen, "Effective Mass in Picosecond Laser-Produced High-Density Plasma in Silicon," accepted for publication in *IEEE Journal of Quantum Electronics,* January 1986.

b. Papers Published in Refereed Journals

N. Bloembergen, Y.H. Zou, and L.J. Rothberg, "Collision-Induced Hanle Resonances of Kilohertz Width in Phase-Conjugate Four-Wave Light Mixing," *Phys. Rev. Lett.* **54**, 186-188 (1985).

A.M. Malvezzi, H. Kurz, and N. Bloembergen, "Nonlinear Photoemission from Picosecond Irradiated Silicon," *Appl. Phys.* **A36**, 143-146 (1985).

H. Kurz and N. Bloembergen, "Picosecond Photon-Solid Interaction," Mat. Res. Soc. Symp. Proc. Vol. 35, Elsevier Science Publishing Company, 1985, pp. 1-13.

J.M. Liu, A.M. Malvezzi, and N. Bloembergen, "Ultrafast Phase Transition of GaAs Surfaces Irradiated by Picosecond Laser Pulses," Mat. Res. Soc.

Symp. Proc. Vol. 35, Elsevier Science Publishing Company, 1985, pp. 137-142.

A.M. Malvezzi, H. Kurz, and N. Bloembergen, "Picosecond Photoemission Studies of the Laser-Induced Phase Transition in Silicon," Mat. Res. Soc. Symp. Proc. Vol. 35, Elsevier Science Publishing Company, 1985, pp. 75-80.

N. Bloembergen and Y.H. Zou, "The Relationship Between Collision-Assisted Zeeman and Hanle Resonances and Transverse Optical Pumping," to be published in *Laser Spectroscopy V*, T. Hansch, Jr. and Y.R. Shen, eds. (Springer, Heidelberg, 1985), pp. 186-191.

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

N. Bloembergen, "Collision-Induced Hanle Resonances in Four-Wave Light Mixing." Invited Lecture at the International Symposium in honor of the memory of A. Kastler, Paris, France, January 1985.

N. Bloembergen, "The Prehistory and Future of Nonlinear Optics." Invited Lecture at the CLEO meeting, Baltimore, Maryland, May 1985, Symposuim for the 25th Anniversary of the Laser.

N. Bloembergen, "The Relationship Between Collision-Assisted Zeeman and Hanle Resonances and Transverse Optical Pumping." Invited Lecture at the seventh International Conference on Laser Spectroscopy, Maui, Hawaii, 1985.

N. Bloembergen, "Collision-Induced Coherence." Invited Lecture at the Symposium on Coherence, Cooperation and Fluctuations, in honor of R.J. Glauber, Cambridge, Mass., October 1985.

II.9 Multiphoton Vibrational Excitation of Molecules. E. Mazur, J. Wang, and K.H. Chen, contract N00014-84-K-0465; Research Unit 8.

Time-resolved Raman spectroscopy of gases at very low densities is used to probe the intramolecular distribution of energy in multiphoton excited molecules. This distribution is studied as a function of time, infrared laser fluence and molecular size. The total overhaul of the experimental set-up, which was started in the previous reporting period, has been completed and the first runs with the new set-up have been performed.

The optical free induction decay cell, which is used to generate short picosecond infrared pulses of controllable duration, was replaced and the plasma

shutter improved. A mode-beat detection and correction system will soon be added to the oscillator. In order to substantially reduce the consumption of gas, a gas-recirculation system was added to the high pressure CO_2-laser amplifier. The unit can now operate without any flow of gas for a period up to a day without substantial loss of gain. This will also allow us to operate with isotopic gas mixtures if needed, e.g. to obtain a higher gain at the weak lines of ordinary CO_2 gas mixtures. A totally new computer-controlled data-acquisition system, consisting of a microcomputer and a CAMAC (computer automated measurement and control) crate, has been interfaced to the experiment. The software has been completely rewritten.

After the overhaul was completed around October, we have first tested the reproducibility of the apparatus by repeating previously reported and published measurements on SF_6 [1]. The measurements reproduced the results obtained previously, demonstrating the reliability of the apparatus. As planned we proceeded then by extending our study to other molecular systems. For $CF_2HC\ell$ preliminary tests in the old apparatus had shown that five Raman active modes of widely different energy can be observed at densities low enough to ensure a collisionless excitation. This molecule, however, absorbs on the edge of the CO_2-laser range at the 9.4 μm R(32) line. At the maximum fluence we could achieve, photoacoustic measurements show that the molecules absorb less than one photon per molecule. At those fluences and excitation levels, no measurable change in the Raman spectrum could be observed.

We are presently carrying out measurements on $C_2H_4F_2$. This molecule has four strong Raman active modes, ranging in energies from 400 to 3000 cm^{-1}, which can be observed in our apparatus. In contrast to $CF_2HC\ell$, however, it absorbs exactly at the peak of the CO_2-laser range, and we are able to cover the entire excitation range from ground state up to the dissociation limit. When the

molecule dissociates a complication arises because the dissociation fragments absorb the ultraviolet from the probing pulse and subsequently emit a broadband radiation, which extends into the anti-Stokes range (this implies that the fragments contain a considerable amount ($> 3000\ cm^{-1}$) of internal energy after dissociation). By monitoring the signal in between two Raman lines it is possible to determine exactly at what infrared laser fluence dissociation starts to play a role. These measurements are being carried out presently. Subsequently we will limit our study of the Raman signals for this molecule to the range of fluences below the dissociation threshold. In addition, the collisional decay of the excitation of the dissociation fragments--which was observed in our first runs and which was seen to vary over different parts of the spectrum--will be studied in more detail.

Reference:

1. E. Mazur, I. Burak, and N. Bloembergen, "Collisionless Vibrational Energy Redistribution Between Infrared and Raman Active Modes in SF_6," *Chem. Phys. Lett.* **105**, 258 (1984).

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PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

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D. Korff and E. Mazur, "Beam Combining Considerations in Stimulated Raman," *J. Opt. Soc. America.*

b. Papers Published in Refereed Journals

H. van Houten, E. Mazur, and J.J.M. Beenaker, "The Temperature Dependence of Flow Birefringence in Gases and the Scalar Factor of Angular Momentum Polarization in Viscous Flow," *Chem. Phys. Lett.* **113**, 135 (1985).

E. Mazur, H. van Houten, and J.J.M. Beenaker, "A Comparison of Data on the Viscomagnetic Effect, Flow Birefringence and Depolarized Rayleigh Line Broadening," *Physica* **130A**, 505 (1985).

E.A. Mason and E. Mazur, "Field Effects on Transport Phenomena in the Transition Regime," *Physica* **120A**, 437 (1985).

i. Honors/Awards/Prizes

E. Mazur, Inclusion in *Who's Who in Frontiers of Science and Technology*, 1985.

III. INFORMATION ELECTRONICS CONTROL AND OPTIMIZATION

Personnel

Prof. R.W. Brockett
Prof. Y.C. Ho
Asst. Prof. P. Maragos
Asst. Prof. R. Suri
Dr. X. Cao
Dr. J. Clark
Dr. Y. Dallery
Dr. J. Loncaric
Dr. A. McIvor
Dr. I. Nikolic
Dr. R. Rubenstein
Dr. K. Wohn
Mr. W. Cebuhar
Mr. D. Cochran
Mr. J. Dille
Mr. V. Eng
Mr. P. Glassman
Mr. W. Gong
Mr. M. Lee
Mr. D. Montana
Mr. Y. Wang
Mr. J. Wu
Mr. M. Zananis

III.1 Conditional Density Approach to Tracking. R.W. Brockett, A. McIvor, K. Wohn, and J. Wu, Contracts N00014-84-K-0465, N00014-84-K-0504, DAAG29-83-K-0027 and AFOSR-81-0054; Research Unit 9.

The problem of determining shape and motion parameters from a sequence of images is basic. We have shown how to formulate problems of this type in terms of the conditional probability density with the conditioning being with respect to the observations. An unexpected outcome of this line inquiry is a new, and rather compelling, argument for the use of edge information, both in conditional density propagation and in simplifying the algorithms. We show that in a certain sense, the complexity of tracking an object as well as possible grows as the length of its perimeter and not as its area. A second aspect of this work involves the development of statistical models for the random aspects of these problems. Here we

have concentrated on questions involving the spatial correlation, or power spectrum, of the various signals involved, including a stochastic description of reflectance. This has led to an interpretation of some well known edge detection filters as "prewhitening filters" in the sense of Bode and Shannon.

Reference:

1. Alan McIvor, Stochastically Based Vision Algorithms, Ph.D. Thesis, Harvard University, June, 1985.

III.2 Analysis of Moving Images. R. Brockett, Contracts N00014-84-K-0504 and N00014-84-K-0465; Research Unit 9.

The first issue is that of obtaining the optical flow (the projection of 3-D velocity vector) from the sequence of time-varying images. So far several researchers have proposed flow computation methods which involve tracking a finite number of feature points which (hopefully) correspond to the structural extrema of objects. Since our motion analysis scheme requires not only the flow itself but also its spatial derivatives, such methods are not adequate for obtaining accurate flow measurements and we are currently investigating two different methods as follows:

Significant intensity changes usually correspond to the texture boundaries and physical edges. By observing the deforming contours over time, one can compute the flow. We have shown that the flow and its derivatives up to second order can be recovered quite reliably, although the flow up to the first order alone will suffice. We have also found that the flow may be much more accurately recovered by utilizing the notion of "temporal smoothness" of flow. According to this model the optical flow is approximated locally as the first-order polynomial in spatio-temporal coordinates.

There are many situations in which contours cannot be extracted or are very sensitive to noise in image. We are studying a complementary approach which

relies on the gray level changes. Under the assumption of convected invariance of image intensity, temporal change of intensity can be measured by the two mechanisms: intensity correlation and spatio-temporal intensity gradient-based. We try to obtain the affine transformation of local image deformation, directly from the intensity change. Such affine transformation will determine the local surface of objects and the global motion parameters as explained in the following section.

The above two different approaches may be combined in order to estimate a more reliable flow field. We propose a multi-resolution approach which (**i**) constructs a pyramid of individual raw image frames, (**ii**) applies the individual methods of flow recovery, (**iii**) determines which method provides the most accurate estimates, and (**iv**) produces the reliable flow field by communication through the various levels of pyramid.

Our approach is based on the optical flow as is viewed as Eulerian description (opposed to Lagrangian). It has been shown that the 3-D motion and object structure (in terms of surface metric and curvature tensors) may be recovered from the optical flow field and its first and second derivatives. However, such an approach involves solving a set of nonlinear equations which are sensitive to noise in the flow. We have developed a new algorithm which is based on the flow field and its first derivatives, over three consecutive frames, under the assumption that the 3-D motion is constant over time and object surface is locally planar. This algorithm relies on solving linear systems of equations and has proven to be robust under the presence of noise.

References:

1. K. Wohn, "Image Deformation: Its Recovery and Utility," Proceedings of International Conference on Advances in Image Processing and Pattern Recognition, Pisa, Italy, December 1985.

2. K. Wohn and J. Wu, "Recovering 3-D Structure and Motion from First-Order Image Deformation," manuscript.

III.3 Probabilistic Methods in Single Frame Picture Processing. R.W. Brockett, J. Clark, and A. McIvor, Contracts N00014-84-K-0465, N00014-84-K-0504, DAAG29-83-K-0027, and AFOSR-81-0054; Research Unit 9.

Many tracking algorithms approach the problem in two stages. The first is that of segmentation and the second is that of nonlinear filtering, using the results of segmentation as an input. Because the errors made in the segmentation process impose a limit on the performance of the system it is important to do this segmentation as accurately as possible. In his thesis [1] McIvor has put the problem of edge smoothing in a filtering context. He models the curve edge detector process with arc length being the independent variable. This process is thus treated as a signal and the output of a crude edge detector is used as the observation process. When the curve is taken to be a process with Gauss-Markov curvature the model equations are bilinear. This situation is shown to give good resuls in specific cases.

Reference

1. A. McIvor, "Stochastically Based Vision Algorithm," Ph.D Thesis, Harvard University, June 1985.

ANNUAL REPORT OF

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers Submitted to Refereed Journals (and not yet published)

R.W. Brockett, "Robotic Hand With Rheological Surfaces," Proceedings of the 1985 IEEE Conference on Robotics and Automation, St. Louis, MO.

R.W. Brockett and J. Loncaric, "The Geometry of Compliance Programming," MTNS Proceedings (to appear).

A. Waxman and K. Wohn, "Contour Evolution, Neighborhood Deformation and Global Image Flow: Planar Surfaces in Motion," to appear in *Intl. Journal of Robotics Research* **4**, MIT Press, 1985.

K. Wohn and J. Wu, "Recovery of 3-D Motion of Local Planar Surfaces from Optical Flow Field," (in progress).

K. Wohn, "Image Deformation: Its Recovery and Utility," to appear in Intl. Conf. Advances in Image Processing and Pattern Recognition, Pisa, Italy, December 1985.

i. Honors/Awards/Prizes

A.M. McIvor, "Stochastically Based Vision Algorithms," Thesis, Harvard University, Division of Applied Sciences, 1985.

T.B. Sanger, "Stereo Disparity Computation Using Gabor Filters," Thesis, Harvard University, Division of Applied Sceinces, 1985.

J. Loncaric, "Geometrical Analysis of Compliant Mechanisms in Robotics," Thesis, Harvard University, Division of Applied Sciences, 1985.

III.4 Discrete Event Dynamic Systems Study. Y.C. Ho, R.Suri, X. Cao, J. Dille, and M. Zazanis, Contracts N00014-84-K-0465, N00014-79-C-0776, NSF-ECS-82-13680, and NSF-CDR-85-001-08; Research Unit 10.

The overall aim of the researches in this unit is to develop analysis, optimization, and control techniques for man-made systems. Our current emphasis is on a class of problems called discrete event dynamic systems. Examples are computer/communication networks, automated manufacturing systems, database under concurrent use, to name just three. Our earlier work in the previous three year funding cycle showed that a new technique called perturbation analysis has considerable promise. The goal here is to attempt the extension and generalization of this technique to a broad class of discrete event systems in analogy to the past successes we had with the more familiar dynamic systems governed by differential equations.

Perturbation analysis provides a very efficient way to estimate the sensitivities of system performances with respect to parameters for discrete event systems. Algorithms have been developed for various queueing networks to obtain these estimates based on only a single sample path. Extensive experiments show that these estimates are quite accurate. Recently, some significant accomplishment concerning the convergence properties of these estimates has been achieved. The convergence theory shows that the estimates obtained using perturbation analysis are strongly consistent, hence justifying the previous algorithms.

Two main performance measures of a closed Jackson network, the system throughput and the mean sojourn times of a customer staying in a particular server or the system, are studied. It is proved that perturbation analysis provides a strongly consistent estimate of the derivative of the expected throughput with respect to the mean service time in a finite period. The elasticity of the throughput with respect to the mean service time converges in the mean to the elasticity of the throughput in steady state as the number of customers served goes to infinity. Similar results hold for the sensitivity of the mean sojourn times. We also developed a set of new equations based on perturbation analysis which calculates theoretically the derivatives of throughput with respect to the mean service time. Numerical solutions show that the results are exactly the same as those obtained by the well-known Jackson formulas.

The sensitivity of mean sysem times of a customer to a parameter of the arrival or service distribution in a M/G/1 queue is also studied. It is shown that perturbation analysis gives asymptotically unbiased and strongly consistent estimates of this sensitivity.

Meanwhile, the mean square error of the perturbation analysis estimates is examined. The error is compared with that of estimates obtained by conventional methods. The results establish the asymptotic superiority of perturbation

analysis over conventional methods.

The convergence property of perturbation analysis estimates for more general systems is now under investigation.

ANNUAL REPORT OF

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers submittted to Refereed Journals (and not yet published)

Y.C. Ho and W.B. Gong, "A Note on Filtering in Queueing Networks and Discrete Event Dynamic Systems," submitted to *IEEE Trans. on Automatic Control.*

X. Cao, "First Order Perturbation Analysis of Multiclass Queueing Networks," to be presented at the 1985 IEEE Conference on Decision and Control, submitted to *Performance Evaluation.*

Y. Dallery and R. Suri, "Approximate Disaggregation and Performance Bounds for Queueing Networks wih Multiple-Server Stations," submitted to PERFORMANCE, 1986.

X. Cao, "On the Sample Functions of Queueing Networks with Application to Perturbation Analysis," submitted to *Operations Research.*

X. Cao and Y. Dallery, "An Operational Approach to Perurbation Analysis of Closed Queueing Networks," Manuscript, Harvard University, September 1985, submitted to 1986 ACC Conference.

M. Zazanis and R. Suri, "Comparison of Perturbation Analysis with Conventional Sensitivity Estimates for Regenerative Stochastic Systems," Manuscript, Harvard University, December 1984, submitted to *Operations Research.*

M. Zazanis and R. Suri, "Estimating Second Derivatives of Performance Measure for G/G/1 Queues Using a Single Sample Path," submitted to *J. Queueing Systems.*

R. Suri, Y.C. Tay, and N. Goodman, "Choice of Performance for Locking in Databases," submited to *ACM Trans. on Database Systems.*

R. Suri and M. Zazanis, "Comparison of Perturbation Analysis with Conventional Sensitivity Estimates for Regenerative Stochastic Systems," submitted to *Operations Research.*

R. Suri and S. DeTreville, "Getting from Just-in-Case to Just-in-Time: Insights from a Simple Model," submitted to *J. Operations Management.*

Y.C. Ho and X. Cao, "Performance Sensitivity to Routing Changes in Queueing Networks and Flexible Manufacturing Systems Using Perturbation Analysis," to appear in *IEEE J. on Robotics and Automation,* 1986.

R. Suri and M. Zazanis, "Perturbation Analysis Gives Strongly Consistent Sensitivity Estimates for the M/G/1 Queue," to appear in *Management Science*, 1986.

Y.C. Ho, "A Survey of Perturbation Analysis of Discrete Event Dynamic Systems," to appear in *Annals of Operations Research*, 1986.

R. Suri and G.W. Diehl, "A Variable Buffer-Size Model and Its Use in Analyzing Closed Queueing Networks with Blocking," to appear in *Management Science*, February, 1986.

R. Suri and J.W. Dille, "A Technique for On-Line Sensitivity Analysis of Flexible Manufacturing Systems," to appear in *Annals of Operations Research*, December 1985.

R. Suri, "An Overview of Evaluative Models for Flexible Manufacturing Systems," to appear in *Annals of Operations Research*, December 1985.

b. Papers Published in Refereed Journals

Y.C. Ho, "Perturbation Analysis of Discrete Event Dynamic Systems," *J. of Optimization Theory and Application* (Leitmann Birthday Volume) **46**, 4, 535-546 (1985).

X. Cao, "Convergence of Parameter Sensitivity Estimates in a Stochastic Environment," 1984 IEEE Decision and Control Conference Proceedings, also *IEEE Transactions on Automatic Control* **AC-30**, 9, 845-853 (1985).

X. Cao, "The Dependence of Sojourn Times on Service Times in Tandem Queues," *J. Appl. Prob.* **21**, 661-667 (1984).

B. Sanders, "A Private/Public Good Decomposition for Optimal Flow Control of an M/M/1 Queue," *IEEE Transactions on Automatic Control* **AC-30**, 11, 1143-1145 (1985).

R. Suri and Y.C. Tay, "Error Bounds for Performance Predictions in Queueing Networks," *ACM Transactions on Computer Systems* **3**, 3, 227-254 (1985).

R. Suri, Y.C. Tay and N. Goodman, "A Mean Value Performance Model for Locking in Databases: The No-Waiting Case," *J. of the ACM* **32**, 3, 618-651 (1985).

R. Suri, "A Concept of Monotonicity and Its Characterization for Closed Queueing Networks," *Operations Research* **33**, 3, 606-624 (1985).

c. Books (and sections thereof) Submitted for Publication

R. Suri and F. Choobineh (eds.), *Flexible Manufacturing Systems: Current Issues and Models*, Institute of Industrial Engineers Press, to appear in 1986.

R. Suri and J. A. White (eds.), "Manufacturing Systems Modelling: Its Role and Current Issues," Chapter in *Research Issues in Material Handling*, Springer-Verlag, to appear in 1986.

d. Books (and sections thereof) Published

R. Suri and K.E. Stecke (eds.), *Flexible Manufacturing Systems: Operations Research Models and Applications*, J.C. Balzer, Basel, Switzerland, 1985.

R. Suri and S. Nof (eds.), "Quantitative Techniques for Robotic Systems Analysis," Chapter in *Handbook of Industrial Robotics*, John Wiley, New York, 1985.

IV. ELECTROMAGNETIC PHENOMENA

Personnel

Prof. T.T. Wu
Prof. R.W.P. King
Dr. J.T. DeBettencourt
Dr. J.M. Myers (after 11/1/85)
Mr. M.F. Brown
Ms. M. Owens
Mr. W.-Y. Pan (until 7/31/85)
Ms. B.H. Sandler

Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical, and experimental techniques and the use of high-speed computers and precision instrumentation. Application is also made of modeling techniques and the principle of similitude. Most practically significant problems in the area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researches are concerned primarily with the properties of antennas and arrays and of the electromagnetic fields they generate in various practically important environments that lead to difficult problems with complicated boundary conditions. Examples include dipoles, traveling-wave antennas and arrays, crossed dipoles, and loops near the boundary between two media such as air and the earth or sea, or the oceanic crust and sea water; the scattering of electromagnetic waves from buried or submerged objects; the properties of lateral electromagnetic waves and pulses; the field inside and currents and charges induced on obstacles within an EMP simulator; arrays of antennas along curved lines; and

solitary electromagnetic pulses with slow rates of decay.

IV.1 Numerical and Analytical Determination of the Fields of Antennas near an Interface Between Two Half-Spaces with Significantly Different Wave Numbers. T.T. Wu, R.W.P. King, B.H. Sandler, and M. Owens, Contract N00014-84-K-0465 and N00014-79-C-0419; Research Unit 11.

The recently derived sets of simple and accurate, analytical formulas for the complete electromagnetic fields of horizontal [1-3] and vertical [4] electric dipoles on or near the boundary between two half-spaces have provided new insight into lateral propagation in general, and more flexible tools for a variety of specific applications. Examples of their usefulness are presented here and under topic #2.

An examination of the new formulas shows that surface waves have unusual properties that make them valuable tools for geophysical prospecting [5,6]. They show that over all distances and at all frequencies a signal reaching a receiving dipole in the salt water near the sea floor has, in effect, proceeded downward from the transmiting dipole in the sea water into the rock, then radially outward in the rock, and finally upward and back into the sea water to the receiving dipole. The decrease in amplitude and change in phase with radial distance depend primarily on the electrical properties of the *rock*. With a suitable choice of frequencies and radial distances ρ between transmitting and receiving dipoles, the received signal can have the simple form $\exp(-\alpha\rho)\exp(i\beta\rho)/\rho$ where α is the attenuation constant and β is the real wave number of the rock. These important facts are the basis for the development of methods for the determination of the conductivity and permittivity of the rock forming the sea floor by means of measurements made in the adjacent sea water. Since lateral waves do not penetrate deeply into the ocean floor, they are useful primarily in determining the average conductivity and permitivity of the material fairly close to the boundary. For this a two-layer theory may be adequate.

The new formulas have also been used [5,6] to assist in the interpretation of available measurements of the conductivity of the sea floor. It appears that the measured data would be well satisfied by a half-space model of the lithosphere that is homogeneous but one-dimensionally anisotropic in the conductivity. Such a model involves no reflections from deeper, widely spaced horizontal layers. An analytical study by W.-Y. Pan of the one-dimensionally anisotropic half-space has been completed which agrees with the available measured data. It is discussed under topic No. 3.

Currently the new formulas are being used to determine certain properties of lateral waves. As a first step in the process, explicit formulas have been obtained [7,8] for the complete field in Region 2 (e.g., air, lithospheric rock) of a horizontal electric dipole located near the boundary in Region 1 (e.g., salt water). Expressions for the field in Region 2 are required in order to determine such properties as the locus of the Poynting vector, the maximum depth of penetration of the lateral wave into Region 2, and the fraction of power associated with the lateral wave. The study is continuing with the determination of the field in Region 2 of the vertical electric dipole.

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IV.2Theoretical Study of Scattering from Buried or Submerged Objects. R.W.P. King, T.T. Wu and W.-Y. Pan, Contract N00014-84-K-0465; Research Unit 11.

The detection and localization of buried or submerged objects or inhomogeneities in a dissipative half-space from measurements of a scattered electromagnetic field are of current interest. Earlier investigations have been concerned primarily with plane waves incident on the surface of the earth from the air above at an arbitrary angle. The present study deals with the incident fields generated by horizontal and vertical antennas located on the surface of the earth. The first step in the analysis is the determination of this incident field. The complete field of such antennas can now be expressed in simple and accurate form with the availability of new formulas (see topic No. 1, refs. 1-4) that are excellent approximations of the rigorous general integrals. In the first of two papers [1], the components of the lateral-wave field at points near the surface in air and at all points in the earth have been determined when the source is a horizontal-wire antenna of finite length located a small height over the earth or salt water. Both antennas with open ends and antennas with ends grounded by vertical conductors are treated.

Once the incident field is known, the scattered field can be investigated. The first scattering object studied is the horizontal insulated conductor [2], since this provides a scattered field that is readily calculated and combined with the incident field to obtain a total field that exhibits interference phenomena. The

incident lateral-wave field is maintained by a horizontal dipole in air just above the surface of the earth, as described above. The total field (incident plus scattered fields) is to be observed also in the air just above the surface. The current induced in the insulated wire by the lateral-wave field incident from the transmitter is evaluated first and then the reradiated field just above the surface is calculated. Two orientations are considered: The field at the center of the buried conductor is (1) parallel to $E_{1\rho}(\rho,0,z)$, and (2) parallel to $E_{1\phi}(\rho,\pi/2,z)$. The incident, scattered and total fields in an area above the conductor have been evaluated for the conditions of a laboratory model. It is clearly demonstrated that a significant change in the electric field over the volume occupied by the scattering object is observed, and that this is sufficiently localized to permit an accurate bounding of the area above the object.

Only a few scattering problems involving very simply shaped targets can be solved analytically. In a separate study by W.-Y. Pan, analytical expressions have been obtained [3] for the scattered field from a buried, perfectly conducting rectangular plate placed parallel to the interface between air and earth. First, the current is expressed in terms of several Tchebichef polynomials of the second kind. The scattered field is the sum of the fields that are generated separately by equivalent horizontal dipoles and multipoles. The moments of the dipoles and multipoles are obtained from the coefficients of the current expansion. These coefficients have been calculated over a frequency range from 13 to 160 kHz and a range of plate sizes from 2 to 20,000 square meters in area.

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IV.3Theoretical Study of the One-Dimensionally Anisotropic Half-Space. W.-Y. Pan, Contract N00014-84-K-0465; Research Unit 11.

Anisotropy in conductivity is found in various stratified media including alternating layers of dense rock with low conductivity and less dense rock with higher conductivity. In such media the conductivity transverse to the bedding surfaces is always smaller than that along the bedding surfaces. A model of horizontally stratified rock in the form of relatively thin layers that alternate with higher and lower conductivities is well approximated by a half-space that is homogeneous but anisotropic in conductivity, with the conductivity $\sigma_z = \sigma_L$ perpendicular to the bedding surfaces different from the conductivity $\sigma_x = \sigma_y = \sigma_T$ parallel to these surfaces. Both σ_L and σ_T are constant. An analytical study of the one-dimensionally anisotropic half-space, beginning with Maxwell's equations and paralleling the analysis for the isotropic half-spaces (see topic No. 1, refs. 1-3), has been completed [1] and compared with recent measurements of the oceanic crust [2]. It confirms the validity of the half-space model with $\sigma_x = \sigma_y = 0.004\text{S/m}$ and $\sigma_z = 0.002\text{S/m}$, and explains the different behavior observed for the E_x and E_y components. Reflections from deeper, widely spaced horizontal layers are not required to explain the observed data. When $\sigma_L = \sigma_T$, the new formulas coincide with those of Wu and King for an isotropic medium. When $\sigma_L \neq \sigma_T$, the lateral wave part of the field is separated into two terms of which the first is of electric type with the wave number $k_2 = k_L$, and the second is of magnetic type with $k_2 = k_T$.

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IV.4Antennas in Material Media near Boundaries and Their Application. R.W.P. King, contract N00014-84-K-0465; Research Unit 11.

Antennas are located on or near the boundary between two electrically different media for many purposes including communication, remote sensing, and geophysical exploration. Their properties and the field they generate are strongly influenced by the proximity of the boundary. Some of the effects of a boundary are conveniently represented in terms of a suitable image. Others, like the lateral-wave fields, are in addition to image effects. This is well understood for vertical antennas erected over the earth or sea [1], and for horizontal wave antennas on the surface of the earth [2]. In a new study [3,4] the properties of antennas embedded in a material medium near a boundary have been determined. In the first paper [3], the theory of the bare metal dipole antenna has been developed in terms of two specific applications: the subsurface antenna for communication between two points below the surface of the earth, and the seafloor antenna for use in studies of the conductivity of the oceanic crust. In the first case, the antenna is embedded in a medium like soil, sand, ice, fresh or salt water near its boundary with air; a frequency range from 30 to 300 kHz is useful. In the second, the antenna is located in the salt water near the oceanic crust under the sea floor; in this case very low frequencies in the range from 0.3 to 3 Hz are needed to penetrate sufficiently into the lithosphere. In both locations, the transmitting and receiving antennas are located in a region of large wave number (Region 1)

adjacent to a region with a much smaller wave number (Region 2).

The principal differences between the antennas near the air surface and those near the sea floor are a consequence of the large difference in frequency. At the very low frequencies used on the sea floor, the internal impedance of the copper conductor is important, whereas it is negligible at the higher frequencies used near the air surface. This means that whereas the bare metal antenna is highly efficient in transferring power from the antenna to the exterior media (Regions 1 and 2) at the higher frequencies, it is subject to an unavoidable large internal power loss in heating the antenna at the low frequencies. The properties of bare copper antennas in the two applications are summarized [3]. These include the distribution of current, the driving-point admittance and impedance, and the effective length.

When the ambient medium in which a bare metal antenna is embedded is conducting, radial currents from the antenna into the medium decrease the axial current. This means that often only electrically relatively short antennas are useful with correspondingly small effective lengths. Radial currents can obviously be eliminated by enclosing the metal cylinder in a dielectric sheath. This greatly changes the properties of the antenna. In the second paper [4], the properties of the insulated antenna in a dissipative medium near a boundary are reviewed. The important effects on antennas of being embedded in media with different properties over a wide range of frequencies are treated spedifically in terms of three examples: (1) A traveling-wave antenna in the earth below air at $f \sim 0.1$ MHz for subsurface communication; (2) an antiresonant antenna on the sea floor at $f \sim 1$ kHz; (3) an electrically short antenna on the sea floor at $f \sim 1$ Hz. The last two are both for geophysical measurements. In each case the current distribution, impedance, input power, effective length, and electric field in the range of interest are determined.

It is shown that the insulated conductor with its various possible terminations (including especially bare monopoles) is a highly effective antenna when embedded in a general dielectric or conducting region with a wave number that is much larger in magnitude that the wave number of the insulating sleeve. Depending on the ratio b/a of the radius of the insulating sleeve to that of the conductor, the insulated conductor acts more like an antenna for transferring power to the ambient medium ($b/a \sim 1$) or a transmission line for supplying power to the terminations ($b/a \geq 10$). At frequencies of 1 kHz and higher, the power loss in the internal resistance of the conductor is negligible and all power is either radiated or transferred to the terminations without loss. At frequencies below 100 Hz, the power loss in the internal resistance becomes dominant and the radiated power transferred directly to the ambient medium negligible small. In this case, the insulated conductor is a highly inefficient transmission line feeding the terminations.

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IV.5Experimental Study of Lateral-Wave Propagation in Layered Media. W.-Y. Pan, Contract N00014-84-K-0465; Research Unit 11.

Current interest in the possibility of investigating the electrical properties of the earth beneath the ocean by electromagnetic means naturally leads to the problem of wave propagation in layered media. A realistic model of the earth's crust typically includes a layer of sediment followed by many layers of rock of various types. Lateral-wave propagation for such cases is much more complicated since a different wave can travel in each of the rock regions and, at the same time, each of the waves is influenced by the neighboring regions. The recent theoretical work of Dunn [1,2] on a three-layer model provides generalized formulas for lateral waves generated by a horizontal electric dipole with unit moment in sea water (Region 1) near its boundary with a medium (Region 2) of arbitrary thickness and having electrical properties intermediate to those of the sea water and the underlying rock (Region 3). His three-layer solution looks very much like the Wu and King two-layer solution. The differences are: (1) there is a sediment term which represents the contribution from the wave traveling in the sediment layer; at distances and frequencies of interest it is negligible; (2) there is a constant A which can change the magnitudes of the fields; and (3) the Fresnel integral now depends on a complicated constant ν.

During this reporting period, experiments corresponding to this three-layer configuration have been performed in the laboratory using a model tank filled with distilled water. The apparatus also included a generator, vector voltmeter, transmitting antenna, and automated movable receiving antenna. The octagonal tank measures 8.5 feet in diameter and 2.5 feet in height. The transmitting antenna is located at the center of the tank; the receiving antenna can move radially outward from the transmitter on a track. Both of the antennas are horizontal insulated linear dipoles, oriented in the radial direction. In order to have the

radial range extend a few wavelengths, the frequency was chosen to be 1.5 GHz.

On the water surface there is a slab supported by four plastic columns. This slab is also octagonal and a little smaller then the tank in size. It consists of one or more sheets of homosote adhered to a slab of styrofoam, 16 cm thick. The layers are held together by plastic bolts and nuts to assure flatness. Initially the composite slab was wrapped with very thin plastic film to keep the homosote dry. After the field had been measured with the dry homosote, the plastic film was removed and the homosote was lowered into the water for three days to absorb water. In the process, the thickness of each sheet of homosote increased from 1.35 cm to 1.6 cm. By weighing a small sample of the homosote, it was estimated that the completely wet homosote slab included 18 percent water. Since the conductivity and relative dielectric constant of the styrofoam are nearly the same as those of air, it is unnecessary to distinguish the styrofoam from the air. The electrical properties of the homosote were estimated to be: $\epsilon_{2r}^{dry} = 2.7$ and $\sigma_2^{dry} = 0.01352$ S/m for the dry homosote; $\epsilon_{2r}^{wet} = 16.61$ and $\sigma_2^{wet} = 0.0993$ S/m for the wet homosote. When the homosote is wet, the electrical properties in the three regions approximately satisfy the condition $|k_1| \geq 3|k_2| \geq 3|k_3|$, as required in Dunn's theory.

The radial electric-field component $E_{1\rho}$ was measured with one, two, and four sheets of homosote in both the dry and wet states and a paper has been written comparing the measured results with theory [3]. The following conclusions have been drawn: (1) The measurements for the wet slab agree quite well with the results calculated using Dunn's theory. The field at the receiving antenna is a lateral wave which is generated by the transmitting antenna, travels up through the middle layer of homosote, then radially forward in the air, and finally down through the middle layer into the water and to the receiving antenna. (2) In the near range, the field with the wet homosote slab will be larger than the

corresponding value without the middle layer. (3) If the thickness of the middle layer is greater then one wavelength in the medium, the amplitude of the wave propagating in the middle layer is not small and the wave will interfere with the lateral wave propagating in the air in a range of distance. (4) When the electrical properties of the middle layer are not very different from those of air (as is the case for dry homosote), the field is similar to that of the two-layer problem.

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IV.6Lateral-Wave Propagation and Modeling of the Lithosphere. M.F. Brown, R.W.P. King, T.T. Wu, and J.T. deBettencourt, Contracts N00014-79-C-0419 and N00014-84-K-0465; Research Unit 11.

Completion of a detailed charting of the transient response of vertical linear monopoles above a metal ground plane has been attained. Groups of transient waveforms have been plotted as a function of antenna length (4 cm, 13.5 cm, and from 20 to 140 cm in various increments) and source-receiver interantenna separations (from 20 cm to 180 cm in 20-cm increments). A quite clean received pulse (one which is very similar in form to Gaussian output of pulse generator) has been measured using a 140-cm tall monopole, and chosen as a reference pulse. A linear telescoping "TV" antenna, when extended beyond 140 cm above its underlying metal ground plane, has been shown to produce little additional improvement in received waveform relative to the reference pulse.

The aforementioned metal ground plane, supported by the walls of a shallow ($\sim$ 1-1/2 ft) wading pool, has been removed to expose an underlying region of salt water with ocean constitutive parameters (σ = 3.5S/m, ϵ_r = 80). Both short (4.0 cm) and tall (140 cm) vertical monopole antennas have been placed in a configuration chosen to replicate the ground plane studies, with one exception. A small metal circular disk ($\sim$ 4 cm in diameter) is used as a conducting plate at the base of the antenna where it contacts the salt water. The conducting plate is supported by vertical rods which extend to the floor of the wading pool. The rods and their base at the wading pool's floor produce a negligible effect upon the field measured in air by the vertical monopole receiver whose bottom tip is $\sim$ 3 cm above the salt-water surface.

The measured waveforms at various source-receiver separations (from 20 cm to 140 cm in 20-cm increments) for vertical monopoles *above salt water* have been shown to be quite similar to those for dipoles above the metal ground plane of the preceding series of data. The center frequency of the received pulses has been measured to be $\sim$ 500 MHz. The pulses undergo a decrement in peak amplitude and a small degree of spreading, with radial distance from the source monopole. The Fourier transforms of all waveforms have been concurrently obtained with plots of $E(t)$ vs. t, and graphed using the waveform digitizer (Tektronix WP2110). The Fourier transforms of the pulses which propagate over salt water indicate that the high-frequency components of the received waveform decrease with source-receiver separation. A paper on the transient response of the vertical monopole over a metal ground plane and over salt water has been presented [1].

Studies are currently underway to categorize the waveform due to *submerged horizontal* pulsed sources in the form of an insulated antenna and broadside arrays of such elements. Although the theory of insulated antennas for use in CW work indicated that they are quite frequency-dependent, a choice of design associated

with the center frequency of the input pulse has yielded a very strong received waveform (using, as in all measurements referred to above, a vertical monopole receiver in a noise-reducing configuration). The received pulse is in the familiar form of a Gaussian field $E(t)$ vs t, and the initial 2-ns wide input pulse undergoes spreading and decrease in amplitude similar to that observed for vertical monopoles above salt water.

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IV.7Fields and Currents and Charges on Obstacles in a Parallel-Plate Simulator at Selected Frequencies and with Pulse Excitation. W.-Y. Pan, R.W.P. King, and T.T. Wu, Contract N00014-84-K-0465; Research Unit 11.

An important first step in understanding the electromagnetic field which penetrates into the interior of a rocket or aircraft through apertures in the metal skin, when this is exposed to an electromagnetic pulse from a nuclear explosion, is the determination of the distributions of current and charge on the outside of the metal surface. For simplicity the shape of the rocket can be approximated by a finite tubular cylinder. The distributions of current and charge induced on such a cylinder by a continuous-wave field have been studied both theoretically [1] and experimentally in the Harvard parallel-plate simulator [2]. A corresponding experimental investigation of the distributions of current and charge induced directly on the cylinder by an electromagnetic pulse has now been completed [3]. Fourier transforms of the observed pulse shapes are taken in order to obtain distributions of a series of frequency components for the current and charge on the surface. These are then compared with theoretical distributions calculated using Kao's

method [4]. The measured data are found to be in basically good agreement with those theoretical distributions induced by the sum of the incident and reflected pulses. Observed differences between measured and theoretical distributions for certain frequency components of the transverse current I_θ are probably due to coupling between the cylinder and the simulator top plate. A quantiative analysis of the interaction between the cylinder and the simulator is difficult and requires further study.

The measured current pulse sequences induced on the vertical cylinder described above have also been compared, in a separate paper [5], with theoretically determined pulse shapes of current induced on an infinitely long conducting cylinder by an E-polarized electromagnetic pulse. For an E-polarized incident electromagnetic pulse with a nonzero direct component, the axially induced current pulse has an infinite direct component and the Fourier integration is divergent. In order to avoid this difficulty, the Laplace transform for the variable t is taken instead of the Fourier transform. After the inverse Laplace transform has been taken, the pulse shapes of the axial induced current can be expressed as the sum of only a few terms. The measured pulse sequences for the finite cylinder closely resemble, in its main features, those of the infinite cylinder but with a series of small reflected pulses added.

The experimental and theoretical investigation of the rhombic simulator under pulse excitation [6,7] indicated that the electromagnetic pulse in the working volume of the simulator is excited by the current in the wires near the source rather than that in the wires near the center of the simulator. This observation is somewhat different from that observed in the frequency domain. The same question must be asked for the parallel-plate simulator: Does the triangular plate near the source also play the most important role in forming the electromagnetic pulse in the working volume of the parallel-plate simulator? To answer this question,

the electromagnetic pulse has been evaluated in terms of the currents on the plates and the roles of currents on different parts of the plates have been analyzed. A paper has been written which clarifies the excitation mechanism of the parallel-plate EMP simulator [8]. It is found that if the length of the parallel plate is short (i.e., close to the height h), the currents on the parallel plate contribute almost nothing to the electromagnetic pulse.

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IV.8Advanced Introduction to Electromagnetic Theory and Its Application. R.W.P. King and M. Owens, and S. Prasad Hinchey of Northeastern University, Contract N00014-K-0465; Research Unit 11.

A new introductory book on electromagnetic theory and its applications has been published by Prentice-Hall [1]. The foundations of electromagnetism are presented in the first six chapters in a manner following that in King's *Fundamental Electromagnetic Theory*--which is now out of print. Applications begin with a chapter on the scattering and diffraction of plane waves by a half-plane and continue with chapters on antennas, electric circuit theory, transmission-line theory, the insulated antenna, the theory of metal waveguides, waves along dielectric rods with reference to optical fiber transmission, and electromagnetic surface waves along boundaries. The presentation stresses the physical interpretation of the mathematical symbolism and the basic unity of the theory. The applications are arranged with increasing difficulty as logical continuations of the theory. They deal specifically with problems of continuing and current interest.

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IV.9Solitary Electromagnetic Pulses with a Slow Rate of Decay. T.T. Wu, R.W.P. King, and J.M. Myers, Contracts N00014-84-K-0465 and N00014-85-K-0616 and DOE Grant DE-FG02-84ER40158; Supplementary Research, Unit 11.

In a recent paper by J.M Brittingham [1], mathematical formulations are developed for "new, three-dimensional packet-line solutions to the free-space Maxwell's equations." These solutions are further characterized as "real, non-singular, continuous functions which propagate in a straight line at light velocity.

They remain focused for all time." It was subsequently shown by Bélanger [2] that a whole family of packet-like solutions of the homogeneous wave equation can be derived that includes Brittingham's form as a special case. Brittingham and Bélanger both observed that pulses of the type formulated, while satisfying Maxwell's equations, carry infinite energy so that they are physically unrealizable. In order to overcome this difficuly, Brittingham [1] supplemented his three-dimensional wave packet by preceding and following surfaces of discontinuity which served to keep the energy associated with the packet finite. Work in this area at Harvard began with the determination [3] that these bounded pulses of Brittingham no longer satisfy Maxwell's equations across the surfaces of discontinuity and are therefore not physically meaningful. The question was then raised whether there are other solutions with the desired properties. In collaboration with Professor H. Lehmann of the University of Hamburg, we have shown [4] under very general conditions that there are no such solutions. In other words, the so-called "focus wave mode" does not focus.

Current research is concerned with the possibility of generating electromagnetic pulses which, while not "focused for all time" like Brittingham's, nevertheless propagate in a manner such that the energy associated with them decreases with the radial distance R much more slowly than as R^{-2}. The justification for the belief that this may be realizable comes from recent advances in particle physics. In particular, it is learned from this work that, even for extremely short wavelengths, a logarithmic dependence of such quantities as the total cross-section on the wavelength can, and does, occur. In the specific formulation proposed recently [5], it is found that the energy received by a given detector must approach zero as it is moved further and further away from the pulse-generating antenna. However, this approach to zero can be much slower than given by the form R^{-2} for an outward-traveling spherical wave. Such cases of slow decrease

are referred to as electromagnetic missiles. Another way of stating the result is that the product of the following two quantities can approach zero as slowly as one wishes: (1) the energy transmitted per unit area of receiver, and (2) the total area of the receiver. Some simple examples of electromagnetic missiles have been constructed [5] when either one, but not both, of these quantities remains finite at infinite distance. Since the rate of decrease with distance of electromagneic missiles can be very slow and they have the advanage of moving with the velocity of light, they have important possible applications.

Since the first example of an electromagnetic missile in ref. 5 involves the current distribution on a circular aperture, a cogent question is: What is the simplest idealized aperture antenna? From the theoretical point of view the suggested answer is the open end of a circular waveguide excited in the transverse distribution characteristic of the lowest mode, the TE_{11} mode. This problem is currently being investigated by Dr. John Myers with ONR support.

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ANNUAL REPORT OF

PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

a. Papers submitted to Refereed Journals (and not yet published)

M.F. Brown and R.W.P. King, "Shallow Sounding of Crustal Regions Using Electromagnetic Surface Waves," *Radio Science.* (Partial support from ONR Conract N00014-79-C-0419.)

R.W.P King, "Electromagnetic Surface Waves: New Formulas and Applications," *IEEE Trans. Antennas and Propagation.* (Partial support from ONR Conract N00014-79-C-0419.)

R.W.P King, "Electromagnetic Surface Waves: New Formulas and Their Application to Determine the Electrical Properties of the Sea Bottom," *J. App. Phys.*. (Partial support from ONR Conract N00014-79-C-0419.)

R.W.P. King, "Antennas in Material Media near Boundaries wih Application to Communictions and Geophysical Exploration. I. The Bare Metal Dipole," *IEEE Trans. Antennas and Propagation.*

R.W.P. King, "Antennas in Material Media near Boundaries wih Application to Communictions and Geophysical Exploration. II. The Terminated Insulated Antenna," *IEEE Trans. Antennas and Propagation.*

R.W.P. King, M. Owens, and T.T. Wu, "Properties of Lateral Electromagnetic Fields and Their Application," *Radio Science.*

W.-Y. Pan, "The Theoretical Analysis of the Pulse Shapes of the Current on an Infinitely Long Conducting Cylinder Induced by an *E*-Polarized Electromagnetic Pulse," *IEEE Trans. Electromagnetic Compatibility.*

W.-Y. Pan, "The Scattered Field from a Buried, Perfectly Conducting Plate in a Lossy Earth," *Electromagnetics.*

W.-Y. Pan, " Surface-Wave Propagation along the Boundary between Sea Water and One-Dimensionally Anisotropic Rock," *J. Appl. Phys.*

W.-Y. Pan, "Measurement of Lateral Waves along a Three-Layered Medium," *IEEE Trans. Antennas and Propagation.*

H.-M. Shen, R.W.P. King, and T.T. Wu, "The Exciting Mechanism of the Parallel-Plate EMP Simulator," *IEEE Trans. Electromagnetic Compatibility.*

b. Papers Published in Refereed Journals

J.T. deBettencourt, "Lateral Waves near the Air-Sea Boundary and Atmospheric Noise," *Proceedings of the IEEE* **72**, 1219 ((1984). (Partial support by ONR Contract N00014-79-C-0419.)

R.W.P. King and T.T. Wu, "Erratum: Lateral Waves: New Formulas for the Magnetic Field [(*J. Appl. Phys.* **54**, 507 (1983)]," *J. Appl Phys.* **56**, 3365 (1985).

R.W.P. King, "Erratum: New Formulas for the Electromagnetic Field of a Vertical Electric Dipole in a Dielectric or Conducting Half-Space near its Horizontal Interface [*J. Appl. Phys.* **53**, 8476 (1982)]," *J. Appl. Phys.* **56**, 3366 (1984).

T.T. Wu and R.W.P. King, "Correction to 'Lateral Waves: New Formulas for E_1 and E_{1z}' by T.T. Wu and R.W.P. King," *Radio Science* **19**, 1422 (1984).

T.T. Wu and R.W.P. King, "Comment on 'Focus Wave Modes in Homogeneous Maxwell's Equations: Transverse Electric Mode' [*J. Appl. Phys.* **54**, 1179 (1983)]" *J. Appl. Phys.* **56**, 2587 (1984).

R.W.P. King, "Scattering of Lateral Waves by Buried or Submerged Objects. I. The Incident Lateral-Wave Field," *J. Appl. Phys.* **57**, 1453 (1985).

R.W.P. King, "Scattering of Lateral Waves by Buried or Submerged Objects. II. The Electric Field on the Surface above a Buried Insulated Wire," *J. Appl. Phys.* **57**, 1460 (1985).

W.-Y. Pan, "An Experimental Investigation of the Distribution of Current and Charge Induced on a Tubular Conducting Cylinder by an Electromagnetic Pulse," *IEEE Trans. Electromagnetic Compatibility* **EMC-27**, 88 (1985).

T.T. Wu, "Electromagnetic Missiles," *J. Appl. Phys.* **57**, 2370 (1985). (Partial support by DOE Grant DE-FG02-84ER40158.)

T.T. Wu and H. Lehmann, "Spreading of Electromagnetic Pulses," *J. Appl. Phys.* **58**, 2064 (1985). (Partial support by DOE Grant DE-FG02-84ER40158.)

d. Books (and sections thereof) Published

R.W.P. King and S. Prasad, *Fundamental Electromagnetic Theory and Applications,* Prentice-Hall, 1986.

g. Invited Presentations at Topical or Scientific/Technical Society Conferences

M.F. Brown, "The Pulsed Lateral-Wave Field of a Vertical Monopole in Air," International Union of Radio Science USNC/URSI Commission F Meeting, Univ. of Massachusetts, Amherst, MA (1985).

R.W.P. King, M. Owens, and T.T. Vu, "Properties of Lateral Electromagnetic Fields and Their Applications," International Union of Radio Science USNC/URSI Commission F Meeting, Univ. of Massachusetts, Amherst, MA (1985).

W.-Y. Pan and R.W.P. King, "Surface Waves along Boundary in Anisotropic Half-Space," International Union of Radio Science USNC/URSI Commission F Meeting, Univ. of Massachusetts, Amherst, MA (1985).

V. SIGNIFICANT ACCOMPLISHMENT REPORT

V.1 Ultra-High-Speed Real-Time Optical Processing Via Convolution and Cross-Correlation in Inhomogeneously Broadened Optical Materials. W.R. Babbit, Y.S. Bai, and T.W. Mossberg, Contracts N00014-84-K-0465, ARO DAAG-29-83-K-0040, and DAAG-29-84-G-0012; Research Unit 6.

The mathematical operation of convolution (or cross-correlation) is known to be important in various applications including radar and pattern recognition. We have developed [1] a new all-optical means of performing convolution which is distinguished by its capability of operating on signals of extremely large bandwidth. In this process, the two waveforms to be convolved are temporally encoded on laser pulses. The two temporally modulated laser pulses together with a third temporally short laser pulse pass successively through an inhomogeneously broadened material having an absorption line at the laser's frequency. The material is thereby stimulated to emit a delayed optical signal whose temporal waveform represents the convolution of the two input waveforms. The bandwidth (duration) of the input signals is limited only by the inhomogeneous (inverse homogeneous) absorption bandwidth of the subject material. In light of typical material parameters, these limits imply that optical signals of microsecond duration and multi-gigahertz bandwidth can be readily convolved. Acousto-optic convolvers currently in use [2] cannot match these bandwidths.

In the last reporting interval, we have performed the first quantitative experimental study of this process. We employed the convolution process to perform mixed binary multiplication at 20 MHz bit rates. These bit rates were limited only by our available laser modulation equipment. On the basis of our measurements, we are able to deduce that in ideal systems convolution signals will be

approximately 1 percent as intense as the input signals being convolved, and therefore be relatively easy to detect.

These results were obtained in the course of our on-going basic study of the interaction of temporally modulated laser radiation with inhomogeneously broadened absorbers. Such interactions are important in a number of potentially useful optical processing and data storage schemes.

References:

1. Y.S. Bai, W.R. Babbit, N.W. Carlson, and T.W. Mossberg, *Appl. Phys. Lett.* **45**, 714 (1984), and W.R. Babbit and T.W. Mossberg, (submitted to *Applied Optics*).

2. L.N. Flores and D.L. Hecht, *Proc. SPIE* **118**,182 (1977), and W.T. Rhodes, *Proc. IEEE* **69**, 65 (1981).

V.2 Electromagnetic Missiles. T.T.Wu and R.W.P. King, Supplementary Research Unit #11A, SOLITARY UNATTENUATED TRAVELING PULSES.

The SDI has generated special interest in the capacity of electromagnetic pulses to carry energy from a high-powered source to a target. A newly formulated electromagnetic wave packet called a "focus wave mode" derived by J.N. Brittingham [1] aroused great interest since it promised a permanently focused three-dimensional concentration of energy that propagates in a straight line with the speed of light. The question was raised: how can it be generated?

A careful study revealed that while the proposed three-dimensional wave packet with its preceding and following surfaces of discontinuity satisfies Maxwell's equations, it does not satisfy the associated boundary conditions [2]. A subsequent extension of this study [3] showed that no solutions with the properties of the "focus-wave mode" can exist; the focus waves do not focus. The

prompt demonstration of this important fact is a significant accomplishment.

Does this mean that the energy associated with an outward-traveling electromagnetic pulse generated by a finite antenna must decrease with distance R as $1/R^2$–the limitation on all continuous-wave propagation? A broadly based investigation of this interesting question has led to the very important result illustrated by specific examples that a decrease in energy with a distance that is much slower than $1/R^2$ is possible.

References:

1. J.N. Brittingham, "Focus Wave Modes in Homogeneous Maxwell's Equations: Transverse Electric Mode," *J. Appl. Phys.* **54**, 1179-1189 (1983).

2. T.T. Wu and R.W.P. King, "Comment on 'Focus Wave Modes in Homogeneous Maxwell's Equations: Transverse Electric Mode' [*J. Appl. Phys.* **54**, 1179 (1983)]" *J. Appl. Phys.* **56**, 2587 (1984).

3. T.T. Wu and H. Lehmann, "Spreading of Electromagnetic Pulses," *J. Appl. Phys.* **58**, 2064-2065 (1985).

4. T.T. Wu, "Electromagnetic Missiles," *J. Appl. Phys.* **57**, 2370-2373 (1985).

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